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40 HP Electro-Mechanical Actuator

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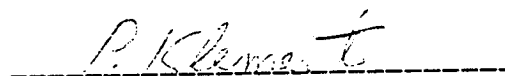
40 HP Electro-Mechanical Actuator Test Report

Contract NAS3-25799

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40 HP Electro-Mechanical Actuator Test Report

AUGUST 1993

1. INTRODUCTION

1.1 Scope

This report summarizes the testing performed on the 40 HP electro-mechanical actuator (EMA) system developed on NASA contract NAS3-25799.

2. TEST CONFIGURATION (ref. Figure 1)

2.1 Test Article

The system under test includes the 40 HP motor controller, the 20 KHz DC to AC inverter, the Sundstrand AC induction motor and Moog actuator.

2.2 Test Equipment

<u>Make</u>	<u>Model / Description</u>	<u>Control #</u>
Doric	412A, Temperature Meter	149169
Fluke	8600A, Digital Voltmeter	X142994-00
Gould	CL-810231-01, Instrumentation Amp	E1040169-14
Gould	RS3800, Strip Chart Recorder	E1040169-00
HP	43A8A, Milli-ohm meter	E142033-00
HP	3466A, Digital Voltmeter	145773
HP	3466A, Digital Voltmeter	E334007-00
Reliance	MC2512AT, Dynamometer Motor	01KA858302-PR
Tektronix	7A22, Differential Amp	HC51879
Tektronix	7A26, Dual Trace Amp	E1040181-00
Tektronix	11A34, 4 Channel Amp	E1040175-00
Tektronix	AM503, Current Probe Amp	147305
Tektronix	AM503, Current Probe Amp	147307
Tektronix	AM503, Current Probe Amp	E1040124-00
Tektronix	DSA602, Digitizing Scope	E1040250-02
Yokogawa	2533, Digital Power Meter	E1040160-00

2.3 Test Plan

Testing was performed in accordance with the "40 HP Task Order System Test Plan" REV 4 dated 7-29-93. The simultaneous measurement of inverter output parameters (power, power factor, voltage and current) and the controller output parameters (power, power factor, voltage and current) was not possible due to lack of availability of two digital power meters.

The system under test was incapable of performing at full power. This shortcoming primarily resulted from the instability of the 20 KHz link voltage. For this reason the system was tested at lower power levels. Measurements were made with a 200 uH per phase choke in the motor's input circuit, except for one test without the chokes.

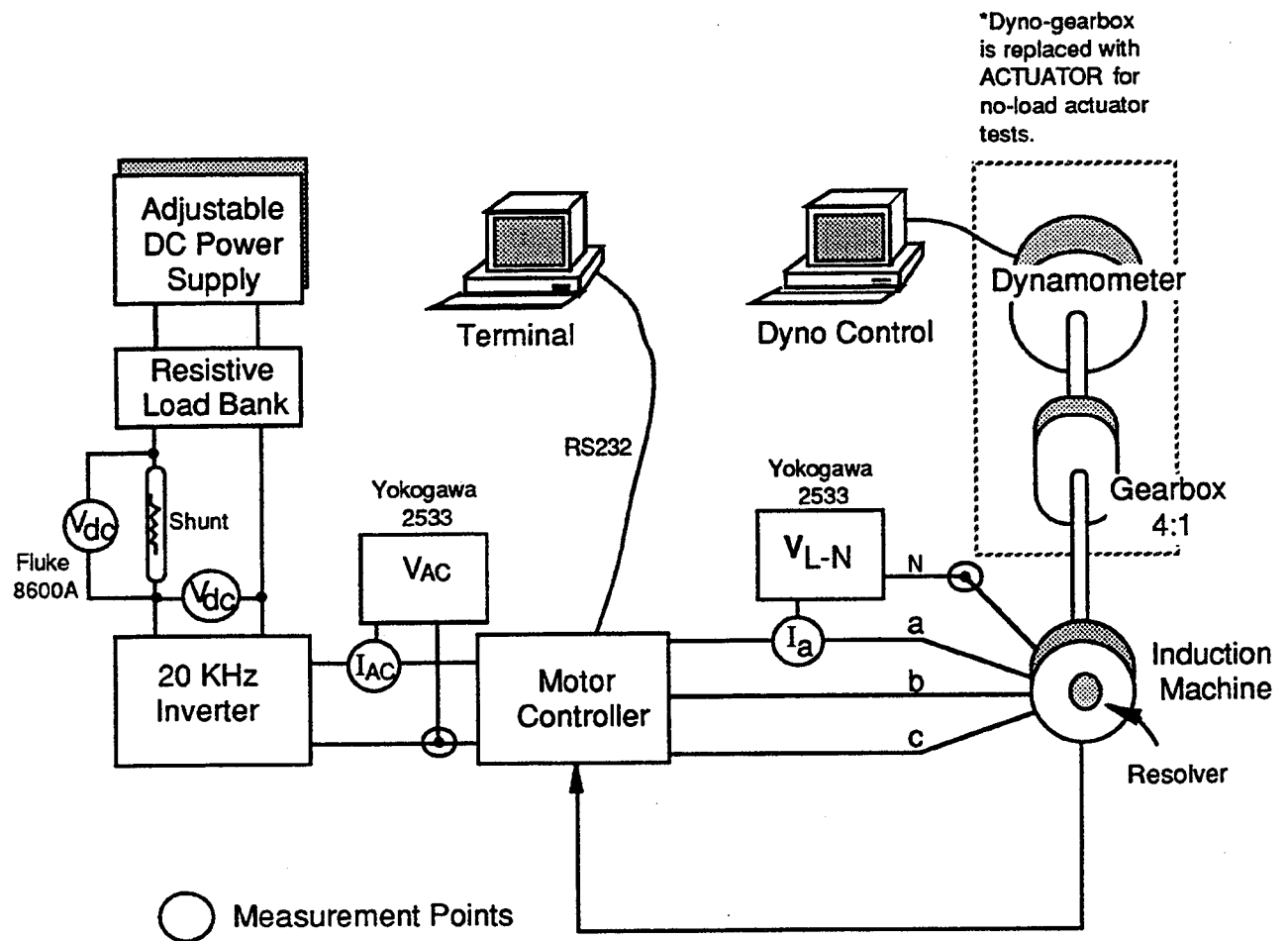


Figure 1; Test Measurement Configuration

3. TEST PROCEDURES AND MEASUREMENT TECHNIQUES

3.1 General

There are four areas in which tests were performed on the system.

- 1) Motor Parameter Tests
- 2) Motor Characteristic Curves
- 3) Steady State Power Loss and Efficiency
- 4) No Load Actuator Tests

Each of these areas required different test procedures and measurement techniques. The specifics are outlined in the test plan and summarized in the following sections.

3.2 Motor Parameter Tests

When performing measurements to determine an induction motor's parameters using a Pulse Density Modulated (PDM) controller as the motor driver, special considerations must be made to ensure accurate results. Of primary importance is the measurement of real power input to the motor.

Real power measurements are required for both blocked rotor and no load testing to determine the Rotor Resistance and Core Loss Resistances respectively. A problem may occur when making these measurements because of the difficulty in resolving the motor voltage to its fundamental frequency components. The PDM controller produces a series of 40 KHz pulses that are integrated by the motor windings to produce a voltage of the fundamental frequency. In order to measure the real power the phase relationship of the voltage and current need to be identified. This is difficult if the motor voltage is a collection of discrete 40 KHz pulses.

A complete description of the motor parameter test procedure is included in Appendix A.

Blocked Rotor Measurements:

The first step in determining the blocked rotor parameters (leakage inductance and rotor resistance; refer to Figure 2, Appendix A) is the determination of R_{eq} (Req = $R_s + R_r$). This parameter is determined from the following relationship: $R_{eq} = \text{Real Power} / I^2$. Because the PDM controller voltage is a series of 40 KHz pulses, the "real power" is most easily measured over the entire spectrum of harmonics. The Yokogawa 2533 digital power meter is capable of this measurement. The Yokogawa 2533 digital power meter is designed to measure complex voltage and current waveforms and then calculate the real and apparent powers using DSP circuitry. This meter is incapable of separating the voltage into individual magnitudes based on their harmonic content however, and therefore cannot be used to measure the fundamental voltage magnitude and phase.

The second step in the determination of leakage inductance requires measurement of the voltage at the fundamental stator drive frequency. Using the

relationship $Z_{br} = V/I$ the blocked rotor impedance (Z_{br}) may be calculated. This impedance is then used to calculate the leakage inductance. This measurement may be performed on the TEK 602 digital signal processing oscilloscope by using a 7A22 differential plugin and the 602's signal averaging functions.

In summary, two types of measurements must be performed to gather the data required to determine blocked rotor parameters. Because of test equipment limitations, this data must be gathered at two different conditions in regard to harmonic frequencies. The "Req" measurement is made with all harmonics present. The "blocked rotor impedance" measurement is made with only fundamental harmonics present.

No Load Measurements:

The same measurement techniques must be used with no load measurements as with blocked rotor measurements. No load measurements are used to determine the core loss resistance (R_m) and the magnetizing inductance (L_m). Measurements of the voltage and real power used in determining R_m are full spectrum in regard to frequency harmonics. The L_m measurements of voltage and current are made at the fundamental frequency. Refer to Appendix A for a complete description of the motor parameter test procedure.

3.3 Motor Characteristic Curves

The motor characteristic curve measurements were made in accordance with the 40 HP Task Order Test Plan, section 3.2.1. The test procedure requires that $I_{ds}=I_{qs}$ for the duration of the test. To accomplish this the motor controller must be modified to allow the I_{ds} output to control the I_{qs} output as well.

The data gathered to generate the curves was collected in two test periods. Ideally all of the data pertaining to the specified measurements should be collected at the same time, but test equipment limitations prevented this option. The measurements were limited by the availability of only one Yokogawa 2533, Digital Power Meter. This piece of test equipment was required to measure both the motor's input parameters (input power, power factor, current and voltage) as well as the inverter's output power, power factor, voltage and current. In practice the 2533 was first used to measure the motor's input parameters at different stator drive frequencies and drive currents. A single phase was measured, but the measurements were confirmed for select operating points on each of the three phases. This data was used to generate the Motor Curves relating to torque, efficiency, power factor and horsepower.

Upon completion of the motor measurements the 2533 digital power meter was connected at the output of the inverter. In this test configuration the remaining measurements to determine inverter and motor controller power stage efficiency were performed. To generate suitable results the second set of data had to be measured with the operating points closely matched to the first set of data points. If not a source of error is introduced. This error is caused by the tendency of the rotor resistance to vary over temperature. If the rotor resistance changes, the corresponding slip value to produce a given torque changes also. This results in a torque error.

The measurements performed minimized this torque error by monitoring the temperature of the stator, and where possible making the measurements at the same temperature as the "Motor Curves" data. If the temperature in the secondary

measurements was difficult to maintain, the slip was adjusted to produce the same torque as in the previous set of measurements. This adjustment was typically small, always less than 0.33% of the slip. This is important because if the slip was substantially changed, the motor's efficiency would change also. The small change in the slip required to match the motor torque output with the previous data will not introduce significant error in this case. This is true because the slope of the motor efficiency / slip curve is small at the measured values, so a small change in slip has little effect on the motor (or system) efficiency.

3.4 Steady State Power Loss / Efficiency Measurements

The steady state power loss / efficiency measurements provide an opportunity to measure the optimum operating point of the system in regard to system efficiency. This was expected to be the point at which $I_{qs} = I_{ds}$. The tests are designed to confirm this while operating the dynamometer in the torque mode.

When operated in the torque mode the dyno maintains a commanded torque load on the motor shaft. Unfortunately, this torque is not constant over different motor speeds. In fact, the commanded torque may vary 70% or more depending on the motor speed. When performing the loss/efficiency measurements the dyno was commanded to provide a given torque load at the low motor speed (3000 RPM). The commanded motor speed was then increased to the next level. The data reveals the expected correlation between operating point efficiency and I_{qs}/I_{ds} .

3.5 No Load Actuator Tests

The no load actuator tests were made in accordance with Attachment A of the Task 13 statement of work. Attachment A is included in Appendix I. For the purpose of conducting the no load actuator tests, the motor was attached to the actuator which in turn was mounted on a table. The testing consisted of two sets of tests. The first tests used a sine wave input signal to measure the systems frequency response and phase shift. This was performed for amplitudes ranging from $\pm 0.1''$ to $\pm 5.5''$. The frequency was varied from 0.05 Hz to 6 Hz. The transient response of the system was measured in the second set of tests. A square wave input signal to the system was adjusted from $\pm 0.25''$ to $\pm 5.5''$ at 0.15 Hz and the actuator's output position was recorded on a strip chart recorder. Additional measurements were also made to study the response of the system at different values of the proportional position constant (K_{pp}).

4. TESTS AND RESULTS

4.1 General

The test data gathered to satisfy the test plan is the culmination of many tests and verifications. In all cases the data was re-measured to confirm the results. In some cases the data was verified 3 or more times. This thorough measurement approach was necessary due to the complex nature of the test article and because of the opportunities for equipment error.

The high harmonic content in the PDM voltage waveform does affect the motor parameters and the performance of the motor. The relationship between motor parameter variations and harmonics frequencies is complex and intertwined with the subtle nuances of motor design. In general there are two types of high

frequency losses that affect our motor parameter measurements; stray losses and time harmonics losses. Stray losses are high frequency losses in the machine caused by space harmonics in the air gap flux wave. Time harmonic losses are accentuated by the high frequency carrier of a PDM drive signal. The extent of these losses in the Sundstrand induction motor and the affect they have on measurement of the motor's parameters and motor performance requires further investigation.

It is important to note that all of the Sundstrand motor testing was performed with a sine wave motor drive, quite different from our PDM controlled motor voltage waveform. We have no error information from Sundstrand in regard to their measurements. References are also made to Sundstrand's "predicted performance" of the motor. These figures were generated by Sundstrand during the design phase of the motor and are included in the "ALS ACTUATOR INDUCTION MOTOR CRITICAL DESIGN REVIEW" dated April 4, 1991.

4.2 Equipment Calibration

All test equipment was calibrated by the calibration laboratory at GDSS prior to testing, or was calibrated as required during the testing. The dynamometer was re-calibrated when certain test results were not repeatable. The problem turned out to be caused by the dynamometer gear reduction unit.

The gear reduction unit has a 4:1 gear ratio which reduces the motor's speed to the maximum dynamometer capability of 3500 RPM. The unit was advertised as having an efficiency of 98%. At the relatively low torque levels our system operates at, however, the gearbox friction was significant. Upon discovery of the problem, tests were performed to characterize the gearbox's frictional losses. These tests revealed that the gear box friction increased as the speed increased and that the friction decreased as the gearbox temperature went up. The results of these measurements are included in Appendix D. All data gathered from the dynamometer was adjusted to eliminate this source of error.

4.3 Motor Parameter Test Results

Rotor Resistance:

Induction motor parameters typically change in predictable ways when the current drive and frequency are varied. The rotor resistance, for instance, increases with increasing slip frequency. This is a natural variation dependent on frequency because of skin effect in the rotor bars. The measured data followed this trend starting with a rotor resistance of 0.0137 ohms (38.2A/phase @ 150 Hz) and increasing to 0.0346 ohms (38.6 A/phase @ 730 Hz). This trend was repeated at different stator current levels. The rotor resistance is also strongly dependent on rotor temperature. For the purpose of the GDSS tests, the motor temperature was maintained at 150 degrees F to minimize errors. The large number of calculations performed in determining the rotor resistance create a worst case uncertainty of up to $\pm 50\%$ of the calculated value. A $\pm 15\%$ error margin may be a better assumption, however, because the worst case scenario is improbable. Note that the rotor resistance is measured during blocked rotor testing with rotor slip = 1.

Sundstrand performed tests on the motor before shipping it to GDSS. The data from their tests was analyzed and used as a source of comparison with our tests. The rotor resistance measurements performed by Sundstrand produced similar

results at the higher frequencies, but showed less correlation at low frequencies. For example the rotor resistance of 0.0342 ohms (39.2 A/phase @ 750 Hz) using Sundstrand's data was very close to the 0.0346 ohms measured by GDSS at similar operating conditions. At a lower frequency of 50 Hz, however, Sundstrand measured a resistance of 0.0253 ohms (30.45 A/phase), a substantially higher value than expected based upon GDSS data. The Sundstrand data may or may not be accurate.

Leakage Inductance:

The leakage inductance is measured as a lump sum of $L_{eq} = L_s + L_r$. The relationship between L_s and L_r is supplied by Sundstrand; $L_s = 1.185L_r$.

In conventionally designed induction motors, the leakage inductance is expected to decrease with increasing frequency. The stator and rotor leakage inductances are also dependent on current magnitude because of local magnetic saturation of leakage paths. Thus, inductance normally decreases with increasing current. The new design methods used in development of the Sundstrand induction motor and the use of a PDM motor controller may result in test results that deviate from past induction motor norms.

The GDSS data shows a slight increase in leakage inductance as the fundamental frequency is increased from 150 Hz to 730 Hz. This increase, however, is overshadowed by the error in calculating the leakage inductance (roughly $\pm 15\%$). There appears no clear correlation between stator current and leakage inductance. In most cases the data indicates that the leakage inductance increases slightly with increasing stator current.

The Sundstrand data does show the leakage inductance decreasing from about 180 μ H to 52 μ H as the slip frequency is increased from 50 to 750 Hertz. The inductance, however, does not decrease with increasing stator currents. The Sundstrand induction motor was designed not to saturate, using Hyperco 50 as the magnetic material. Both the Sundstrand and GDSS data appear to confirm that this design goal was accomplished, as the leakage inductance remains relatively constant for different stator currents.

In some areas the GDSS data and the Sundstrand data agree closely. An example of this is that the single phase blocked rotor input impedance (Z) data is roughly equal for both sets of data. For example; GDSS @ 488 Hz and 38.7 A $Z=0.176$ ohms, @ 730 Hz and 63 A $Z=0.254$; Sundstrand @ 500 Hz and 26.6 A $Z=0.183$ ohms, at 750 Hz and 58.9 A $Z=0.251$ ohms. Looking at a graphical representation confirms this trend over different stator frequencies (ref: "Motor Z, 35A" chart in Appendix C). This chart demonstrates that in the 33 A to 39 A range the motor impedance is similar for both sets of measurements.

Core Loss Resistance:

Core loss resistance values depend on the flux level and frequency. In general the core loss is near its maximum value near the rated motor flux. These trends are evident in the Sundstrand test data but if present in the GDSS test data, are obscured by the error (roughly $\pm 15\%$). The core losses associated with high frequency time harmonic drives are difficult to predict. There are a number of factors when using the PDM drive that combine to influence the motor

performance based on motor and controller design. Discussion of these factors is beyond the scope of this report, but reference material is available in the University of Wisconsin-Madison, ECE 411 Electromechanical Systems course notebook.

Magnetizing Inductance:

In conventional induction machines the magnetizing inductance is dependent on the current magnitude because of saturation of the main flux path. The trend is one of decreasing inductance with increasing motor flux. Once again, this is dependent on the specifics of the motor design and the Sundstrand motor is designed to saturate a much higher flux levels than previous designs. The GDSS data appears to follow this trend with the magnetizing inductance decreasing by roughly 2% to 7% depending on the operating frequency. The noise due to measurement error ($\pm 16\%$) clouds this picture however. The Sundstrand data also appears to follow this trend of decreasing magnetizing inductance with increasing current (and consequently motor flux). In both cases the reduction in the inductance with increasing motor flux is minimal and attests to the superior performance of the Sundstrand motor design.

4.4 Motor Curves Test Results

The motor curves test data was gathered in two different measurement sessions. The first session measured the input and output of the induction motor at different slip values. This information is represented in tabular form as well as graphical form in Appendix E. The graphs or charts show the variations of torque, efficiency, power factor and horsepower relative to rotor slip. The measurements were made at four stator current levels of about 40, 50, 60, and 70 Amps per phase with $I_{qs}^* = I_{ds}^*$. The Yokogawa 2533 digital power meter was used to measure the power into the motor. The dynamometer was used to measure the power out of the motor. The dynamometer gear box was a source of error. The gearbox friction losses decrease with rising temperature and increase at greater speeds. The trend has been measured and is documented in Appendix D. All of the output torque measurements were calibrated based on the temperature and speed of the gearbox.

Sundstrand performed a simulation of the motor's capabilities as part of their design procedure. This data is used as a sanity check on the motor data gathered. The simulation indicated the following operational maximums:

Efficiency (%)	89.9
Power Factor	0.85
Torque (In-lbs)	380.0
Horsepower	69.3
Current per Phase	210.4

The measured data does not achieve these levels because of limitations in the power output of the inverters and the motor controller. The 20 KHz inverters have been tested to deliver 37 KW into a resistive load. This provides a maximum capability of about 36 HP output from the motor if efficiencies are as predicted: $\text{Power Out} = \text{Inverter Power Output} \cdot \text{motor controller efficiency} \cdot \text{motor power factor} \cdot \text{motor efficiency} = (37\text{KW}) \cdot 0.95 \cdot 0.85 \cdot 0.9 / 746 = 36 \text{ HP}$. Our data has shown that maximum power factor, efficiency and torque do not occur at the same operating point, consequently maximum power output will be lower. In addition

the instability of the 20 KHz link voltage has prevented testing the system beyond about 15 HP. The charts in the Sundstrand CDR package include motor operational data at lower power levels closer to our range of operation.

A comparison of the Sundstrand torque simulation data to the measured torque raises some questions. The Sundstrand data shows that with an input of 70 A per phase the motor's output torque is expected to be about 70 in-lbs. This is more than 20% higher than the 57 in-lbs or so torque value we measured at 70 A/phase. Measurement error variations (± 3 in-lbs error on motor torque, ± 3.1 A error on current) are too small to account for these differences. Sundstrand's torque per ampere data is also substantially higher than the GDSS data. The Sundstrand Torque / Ampere - Slip Frequency Curve suggests that ratios of 1.2 to 1.5 in-lbs/Amp are achievable. Our test data produced Torque / Ampere ratios as high as 0.9 in-lbs/Amp.

The discrepancy in the predicted and measured torque per ampere values may be explained by the current regulator in the motor controller. The present current regulator is a "bang bang" regulator. The circuitry is designed to respond to discrete current level changes only. If the current is within range of its "window" no action is taken. A simulation performed by Kraus and Associates for NASA LeRC indicates that in the 40 HP system, a significant limitation in the torque output of the motor can be expected with this type of current regulator. Kraus and Associates suggested the incorporation of a PI current regulator into the hardware to correct this deficiency.

Motor power factor and efficiency measured lower in practice than the simulated data predicted. The maximum power factor achieved under test was $0.63 \pm 0.5\%$. Typical simulated values for the power factor fell into the 0.75 to 0.8 range. Power factor is strongly affected by motor current magnitude however, and our tests were performed at points below the motor's maximum current ratings. Extrapolating GDSS data to higher stator currents indicates that the power factor is likely to reach predicted levels at higher current levels.

The motor's efficiency reaches a maximum of about 80 % at 70 Amps per phase and 14,000 RPM. The motor's top rated speed is 14,700 RPM, the point at which Sundstrand predicted 89.9 % efficiency. We were unable to test the motor beyond 14,000 RPM due to limitations of the gearbox and dynamometer. The motor efficiency measurement error of ± 10 % is significant in this case, since the predicted motor efficiency falls within this window. It is likely however, that the motor is capable of higher efficiencies at higher speeds and stator currents.

The second set of tests measured the input power to the motor controller power stage and the DC input power to the inverter at several operating points. These operating points were selected to be the same as those measured in collecting the motor per phase data in the first set of tests. The resulting data provides the information necessary to determine inverter, power stage and system efficiencies. This data is in Appendix E. The discussion of measurement errors in section 5 is very important when considering these results.

One test was performed to assess the performance of the system without the 200 uH per phase chokes, in the motor circuit. The results of this test are included in Appendix F. Without the chokes in the circuit, the power factor and efficiency fall by about 50 % and 35% respectively. The torque decreases by about 20%. The

motor current waveforms without the chokes in the circuit have a much larger high frequency component. The extra high frequency energy is dissipated in the motor in the form of heat. The distorted current waveforms produce a lower average power factor and generate less torque.

4.5 Steady State Power Loss / Efficiency Test Results

For the purpose of these tests the slip constant (K_s) was adjusted to 0.07, the average value that produces the most efficient operation under typical operating conditions. The Steady State Power Loss / Efficiency tests confirmed that the highest efficiency operation occurs when $I_{qs}^* = I_{ds}^*$. The data sheets and associated charts in Appendix G illustrate this fact. The system efficiency scale (on the right of the chart) represents the % system efficiency. I_{ds}^* and I_{qs}^* are scaled on the left side of the chart. The lower torque values for a given motor speed provide a better picture of the efficiency vs I_{ds}/I_{qs} because there are more data points. The higher torque levels prevent the system from maintaining the commanded torque without higher currents and consequently fewer data points.

It should be noted that several parameters are changing simultaneously in this series of tests. Although the I_{ds}^* is at a level commanded by the operator, the I_{qs}^* and consequently the motor slip is allowed to adjust as required to maintain the commanded torque load. The slip value is calculated based upon the values of I_{qs}^* , I_{ds}^* and the motor parameters using the relationship;

$$\text{slip frequency} = R_r \cdot I_{qs}^* / L_r \cdot I_{ds}^*.$$

It can be seen from this formula that the slip frequency will increase as I_{ds}^* is decreased.

4.6 No Load Actuator / System Test Results

The no load actuator testing confirmed previous test data obtained at NASA Marshall Space Flight Center (September 1992). The response of the system is dependent on the control gain constants, commanded amplitude and output power levels. As specified in the No Load Actuator Test Procedure (Appendix I), the frequency response was measured using a sine wave input and the step response was measured using a square wave input. For the purpose of these tests the sine wave data was recorded with the proportional position constant (K_{pp}) equal to 14.3 and the proportional rate constant (K_{pr}) equal to 1.53 unless otherwise noted. The large signal step response was measured with K_{pp} equal to 5.0 and K_{pr} equal to 1.53. Additional frequency response and transient response tests were also performed, while varying the control gain constants, to document their effect on system response.

The frequency response of the system is best determined by identifying the frequency at which the phase delay is equal to 90 degrees. The command/position phase shift changes quickly approaching the pole in this second order system. For this reason, data was gathered at 0.1 Hz intervals from 3.0 to 4.0 Hz, the predicted range of the cutoff frequency. Evaluating this data the 90 degrees phase shift occurs at 3.2 Hz and ± 0.1 " amplitude (70 A/phase) with an amplitude gain of 0.6. The response of the system falls off rapidly at frequencies above 3.2 Hz. At larger amplitudes and lower phase currents the cutoff frequency is lower.

The control loop constants may be adjusted to achieve optimum system response for differing conditions. A larger value for K_{pp} improves the small signal response but causes overshoot or instability at higher amplitudes. This is demonstrated in the sine wave position vs. command plots for $1.0 \text{ Hz} \pm 0.5''$ and $2.0 \text{ Hz} \pm 0.1''$. The data was gathered at $K_{pp} = 9.0$ and 14.3 . The higher position loop gain of 14.3 at a $\pm 0.5''$ amplitude causes a significant overshoot and phase delay. The response is markedly better with $K_{pp} = 9.0$. At a lower amplitude of $\pm 0.1''$ however, the response is superior when $K_{pp} = 14.3$, with less phase shift and higher gain.

Of special interest is the step response data ($\pm 1.0''$) gathered while varying K_{pp} from 1.0 to 14.3 . Sluggish response is apparent when $K_{pp} = 1.0$, critical damping occurs when $K_{pp} = 5.0$, and considerable overshoot is present when $K_{pp} = 14.3$. In practice these control constants may be dynamically varied to optimize the response, dependent on the operating conditions.

5.0 MEASUREMENT ERROR

5.1 Principle Sources Of Error

Torque Measurement Error (at motor)	$\pm 3 \text{ in-lbs}$
Yokogawa 2533 Power Meter Accuracy (Tested at GDSS)	$\pm 2 \% \text{ of full scale}$
AC Voltage Measurement Error	$\pm 0.37 \% \text{ of input} + 0.03\% \text{ of range}$
DC Voltage Measurement Error	$\pm 0.02 \% \text{ of input} + 0.008 \% \text{ of range}$
DC Current Measurement Error	$\pm 0.1 \% \text{ of input} + 0.01 \% \text{ of range}$
Motor Speed Measurement Error	negligible
Motor Fundamental Frequency Voltage Error	$\pm 5 \% \text{ of measured value}$
Temperature Measurement Error	$\pm 1 \text{ degree C}$

5.1 Error Assessment

The assessment of error in determining motor parameter values and system efficiency values is complex. The magnitude of the errors depends on several factors. The measurement error changes with the operating point of the system because the Yokogawa power meter for example, specifies accuracy as a percentage of the range. The range changes during the measurements depending on the magnitude of the voltage and current. But for a given range, the measurements made on the low end of the range have a greater error associated with them. Power is particularly difficult to measure with a high level of accuracy. The available test equipment is capable of making real power measurements to an accuracy of between 2% and 20% in our test application. This is due to both the range in which the voltage and current magnitudes fall and the poor power factor environment in which many of the measurements were made. At the low power factors, power factor measurement error increases to about 4% on the Yokogawa 2533.

Some of the measurements have errors specified to a percentage of the measured value as well. The digital multi meter's errors are specified in this way. This requires a multi-step process when determining the total measurement error.

Another important consideration is the number of arithmetic calculations that are performed using the data. Each successive calculation accumulates the errors from the preceding computations. The very nature of the motor parameter determination requires numerous calculations to arrive at the end values, which consequently have large error uncertainties.

There are two types of error sources; Random Errors and Guarantee Errors. Random errors are the result of unknown or unpredictable forces that result in measurements varying from reading to reading on a given instrument. These types of errors may be analyzed using statistical methods. Guarantee errors are errors attributed to the capabilities of a piece of test equipment. Providing that the equipment is properly calibrated, all measurements will be within a specified error range. In determining the error associated with each measurement or calculation, these errors are treated differently. Random errors may be added using the root-sum-square techniques available in statistical theory while guarantee errors must be added algebraically.

The analysis of our data has revealed a potentially high variance of the values due to errors. It is important to keep in mind that these error numbers are a worst case calculation dictated by the standards of error analysis. This is not the likely error as it is improbable that all error components will be in their worst case condition at the same instant. In fact the actual error is a probably a fraction of the worst case scenario. Examples of the worst case error analysis are included in Appendix H.

5.2 Torque Transducer

The Eaton model 1105 torque transducer and it's associated Daytronic 3178 signal conditioner are integrated into the dynamometer assembly. They measure and transmit the motor's torque output (after a 4:1 gear reduction) to the dyno control terminal. There are several sources of error in this equipment. The torque transducer error is made up of nonlinearity, hysteresis, and repeatability errors of $\pm 0.1\%$, $\pm 0.1\%$, and $\pm 0.05\%$ of full scale, respectively. The full scale measurement capability of the torque transducer is 5000 in-lbs. The Daytronic signal conditioner has an error of $\pm 0.05\%$ of full scale. The torque transducer errors are considered random errors and consequently the total error is determined from their root sum square ($RSS = 0.15$). Including the signal conditioner error, the sum of these errors is $\pm 0.2\%$, corresponding to ± 10 in-lbs accuracy in the **dyno** torque measurement. The **motor** torque measurement error is ± 2.5 in-lbs (The 4:1 gearbox separating the dyno from the motor results in a corresponding reduction in motor torque measurement error). Additional error is introduced in measuring the motor torque due to the gearbox nonlinearities. The total accuracy in measuring motor torque is ± 3 in-lbs including these gearbox variations.

5.3 Power Measurement Meter Accuracy

The Yokogawa model 2533 digital power meter has a voltage, current and power measurement accuracy of $\pm 2\%$ of the range up to frequencies of 20 KHz, as specified by Yokogawa. The manufacturer has not measured the accuracy above this frequency, so we measured the voltage and current frequency response of the unit up to 400 KHz. Those measurements were within $\pm 2\%$ of our calibrated reference

signal. The power factor accuracy is specified as $\pm 0.5 \%$ at a 0.5 PF and 60 Hz. The power factor measurements were verified at several frequencies ranging from 100 Hz to 700 Hz on the Tektronix DSA 602 oscilloscope. At low power factors, however, Yokogawa relaxes this specification to $\pm 4 \%$ (PF=0.1). The power measurement accuracy is based on the selected range of the measurement instrument. For our tests the current range was always 155 A, dictated by a current transformer used with the test set up. The voltage range changed depending on conditions. The following is a summary of the voltage, current and power measurement errors attributed to the Yokogawa 2533 voltage range setting.

<u>Voltage Range (V)</u>	<u>Voltage Error (V)</u>	<u>Current Error (A)</u>	<u>Power Error (VA)</u>
30	± 0.6	± 3.1	± 93
60	± 1.2	± 3.1	± 186
100	± 2.0	± 3.1	± 310
150	± 3.0	± 3.1	± 465
600	± 12.0	± 3.1	± 1860

The accuracy of the power measurements included in the data are on average good to about 10 %. The error is higher than 10 % on low power factor measurements and those power measurements made on the low end of the range of the instrument. The error is heavily dependent on the voltage range selection because the power error numbers given above are fixed relative to a given range. For example, if power is measured as 3000 watts with the voltage range set to 600 volts, the error is 3000 watts ± 1860 W or $\pm 62 \%$. Due to this limitation all measurements are performed with the instrument's range adjusted to minimize this error. In certain low power, high voltage situations, however, this result is unavoidable.

5.4 Digital Meter Accuracy

The digital voltmeters used in the DC measurements were highly accurate relative to the AC power meter capabilities. In practice the DC input power to the inverter was measured using a Fluke 8600A DVM in the DC voltage mode. Input current was measured as a voltage on the 200 mV range by using a precision 0.0004949 ohm shunt resistor. The inverter input voltage was measured on the 1200 volt DC scale. These measurements are accurate to $\pm 0.02 \%$ of input + 0.008 % of the range.

5.5 Motor Fundamental Frequency Voltage Error

The magnitude of the voltage at the fundamental stator drive frequency was measured to allow the calculation of motor parameter values. This signal is a series of 40 KHz pulses that comprises the PDM motor voltage. In order to measure the fundamental frequency voltage the signal required filtering to produce stable measurements. A Tektronix 7A22 differential amplifier was used in conjunction with a Tektronix DSA 602 scope. The 7A22 has a filtering function with selectable filter cutoff frequencies. For the purpose of these tests the differential amplifier was configured as a low pass, 1 KHz filter. The differential amplifier was then calibrated up to 1 KHz to compensate for the attenuation of signal levels at frequencies below the high frequency cutoff point. The DSA 602 scope's signal averaging functions (X8) were utilized to obtain a stable, steady state value for the voltage measurement. The combination of noise, calibration accuracy, equipment specifications and signal stability limit the voltage measured using this method to $\pm 5 \%$ of the measured value.

5.6 No Load Actuator Test Error

The measurements involved in performing the No Load Actuator Tests are relatively simple and not subject to large errors. Two signals are measured; the command amplitude, phase and frequency, and the actuator position amplitude, phase and frequency. These measurements are performed and documented on the strip chart recorder, and verified on the DSA602 scope. The DSA602 is also used to plot the position / command, X-Y plots. The source of the signals are identical D/A converters located in the motor controller card cage. These D/A converters monitor both the input command voltage and the actuator position. The D/A converters were calibrated to one another prior to the testing to an accuracy of ± 5 mV. Most of the measurements were in the ± 1.0 v to ± 10.0 v range so the D/A accuracy is negligible. The small signal measurements in the 150 mV range were more susceptible to random noise present in the environment. This is noticeable on the X-Y plots as random data points. The strip chart recorder was particularly adept at reducing environmental noise. Its differential inputs and noise filters effectively eliminated this noise from the plots. The steps that are noticeable in the small signal position traces are caused by the 5 m/Sec update time of the D/A converters. The total error associated with the no load actuator tests is about $\pm 3\%$.

5.7 Cumulative Calculation Errors

Appendix H, Worst Case Error Analysis, contains examples of the error analysis applied to the experimental data. These calculations demonstrate the large errors that result from the cumulative affect of errors in successive calculations. These error margins should be considered as a worst case probability only, when evaluating the test data. The realistic value for error margins is significantly less than the worst case error analysis indicates. Measurements made at low powers, high voltages relative to range and low power factors have greater maximum errors. In general, most of the calculated values are accurate to within 10 % of their stated values.

6.0 CONCLUSIONS

The series of tests performed have verified the operation of the 40 HP system up to about 15 HP. Although this is below the rated capability, the data indicates that the system is operating properly from a functional standpoint. The operational limits of the system were not reached in testing due the limitations of the 20 KHz power source and 20 KHz link stability. It is estimated that with the presently available 20 KHz inverters as a source of power, the system is capable of producing about 30 HP to the load, when the 20 KHz bus voltage is stabilized. The power is limited by efficiency and power factor limitations inherent in the system, and the 37 KW maximum capacity of the present inverters.

The motor tests show that the motor parameters are within the expected range, based on testing performed by Sundstrand at their factory. The error associated with our motor parameter measurements and subsequent calculations makes precise determination of the motor parameters difficult. These measured values do however, provide a range of certainty in which the motor's parameters are known to fall.

Testing to generate the motor's characteristic curves confirmed that the maximum torque, power factor and efficiency occur at different rotor slip values. Maximum system efficiency occurs when I_{qs}^* is equal to I_{ds}^* . Testing also revealed that the system may not be producing the motor torque it should, based on predictions from the motor's manufacturer. The test data indicates that the torque may be as much as 20% too low for a given input current. Simulations performed by Krause and Associates for NASA, identified this as a potential problem due to limitations in the current regulator. This area requires further investigation.

The overall system efficiency was tested at a maximum of about 65 %. The motor efficiency peaked at 80 %. Inverter and controller power stage efficiencies measured as high as 85 % and 95% respectively. All of these numbers are expected to increase at higher power levels and motor speeds. In general, the efficiency calculations are good to approximately ± 5 %, although worst case analysis indicates about ± 10 %. All of these efficiencies are in the range anticipated for the system. The inverters in particular have been confirmed in previous tests to achieve 93 % efficiency into a resistive load at full power. Power loss analysis of the controller power stage predicted > 90 % efficiencies.

The no load actuator tests indicated a system frequency response of 3.2 Hz at $\pm 0.1^\circ$ and 70 A/phase. This agrees with the data gathered at NASA Marshall (9/92). The frequency response of the system is less at higher amplitudes or lower phase currents. The frequency response of the system may be adjusted by changing the control constants or the phase currents as demonstrated by the test data. Adjustment of these parameters is available via the computer terminal interface. The no load actuator test data is accurate to, at worst, about $\pm 3\%$.

The worst case error analysis revealed potentially large deviations in the measured motor data. The errors may be attributed to two areas. The first is the relative inaccuracy of the AC power measurements. The available test equipment (Yokogawa 2533) is specified as 2 % accurate at full scale and high power factors. Our system often operates at lower power factors and fractions of the full scale meter readings. This results in potential errors of about 10 % of the measured values. Secondly, most of the data is used in successive calculations which magnify these errors. The resulting motor parameter values for instance are the culmination of four or more algebraic solutions. These types of errors require an algebraic solution as well, which is typically large, although not necessarily realistic. Accordingly, the worst case error analysis numbers should be regarded as the unlikely outside limits of certainty.

APPENDICES

<u>Appendix</u>	<u>Title</u>
A	Motor Parameter Test Procedure
B	Motor Parameters Test Data; GDSS and Sundstrand
C	Motor Impedance Comparison; GDSS and Sundstrand
D	Gear Box Friction Calibration Data
E	Motor Curves Test Data and Charts
F	System Efficiency Data
G	Loss/Efficiency Data
H	Worst Case Error Analysis
I	No Load Actuator Test Procedure
J	No Load Actuator Test Data

APPENDIX A

Motor Parameter Test Procedure

Appendix A; Motor Test Procedure

Measuring Induction Motor Parameters:

Measuring induction motor parameters with a Pulse Density Modulated (PDM) motor controller requires specialized test procedures. The procedures outlined here are required to achieve accurate measurements of the Stator Leakage Inductance (L_s), Rotor Leakage Inductance (L_r), Magnetizing Inductance (L_m), Rotor and Stator resistances (R_r and R_s), and Core Loss Resistance (R_m). The high harmonic content of the drive voltage and to a lesser extent, the drive current that are characteristic of a PDM drive make the following test procedure necessary.

Blocked Rotor Testing:

The goal of Blocked Rotor Testing is to identify the leakage inductances of the motor and the rotor/stator resistances. With the rotor blocked (held motionless) the single phase induction motor model reduces to only equivalent resistances and leakage inductances. This occurs because when the slip goes to 1 (with the rotor blocked), the magnetizing resistance and inductance are effectively shorted out by the small values of rotor resistance and leakage inductance.

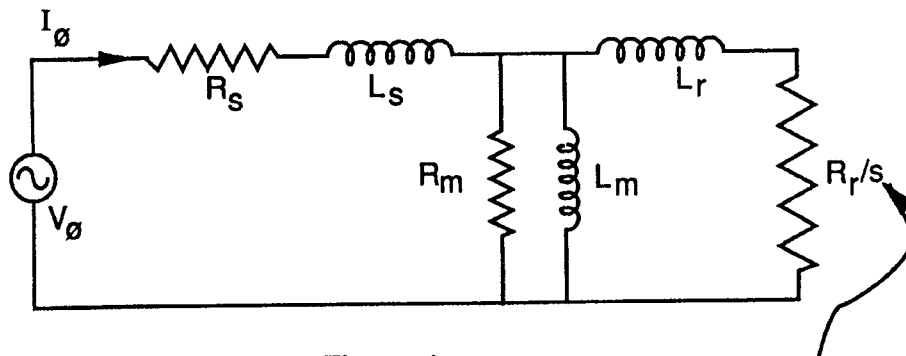


Figure 1

When $S = 1$ model reduces to:

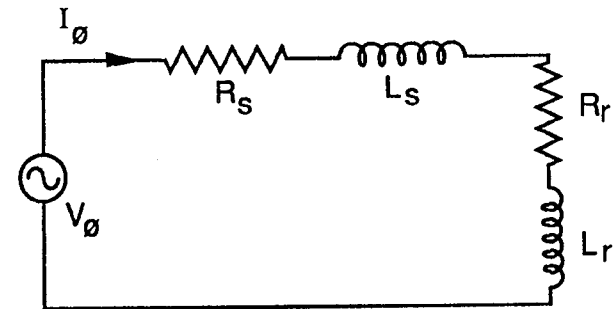


Figure 2

Appendix A; Motor Test Procedure

Blocked Rotor Measurements:

- 1) Measure the stator resistance (R_s) with a resistance bridge or milliohm meter. The measurement should be performed on all three phases of the induction motor from Line to Neutral, at different temperatures.
- 2) Measure the Real or Effective Power and the current into the motor on a per phase basis. These measurements should be made over a range of input currents and drive frequencies. Using the data gathered in this test the equivalent resistance ($R_{eq} = R_r + R_s$) may be calculated. This measurement should be made with test equipment capable of reading the entire harmonic spectrum produced by the PDM controller.

$$R_{eq} = \frac{\text{Real Power}}{I^2}$$

$$\text{Then to calculate } R_r: R_r = R_{eq} - R_s$$

- 3) Leakage Inductance: This measurement requires that the per phase voltage and current be determined at the motor's fundamental test frequency. This is necessary because the leakage inductance is measured indirectly using the blocked rotor impedance and then computed from the following formulas:

$$\text{A) Calculate the Blocked Rotor Impedance } Z_{br}. \quad Z_{br} = \frac{V}{I}$$

$$\text{B) Calculate the inductive reactance } (X_L) \text{ from } Z_{br}.$$

$$X_L = \sqrt{Z_{br}^2 - R_{eq}^2}$$

$$\text{C) Calculate the equivalent leakage inductance } L_{eq} = L_r + L_s:$$

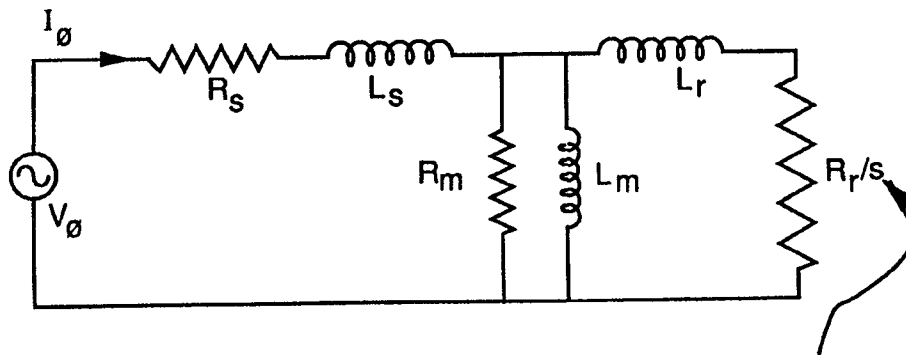
$$L_{eq} = \frac{X_L}{2 \pi F}$$

Note: The voltage and current measured in step (A) must be the motor drive fundamental frequency. With a PDM controller the fundamental frequency component of the voltage is difficult to measure because the voltage is a series of pulses. Signal filtering or signal processing is necessary to identify the magnitude of the fundamental voltage component.

Appendix A; Motor Test Procedure

No Load Testing:

The goal of No Load Testing is to identify the magnetizing inductance and the core loss resistance of the motor. When the motor is running with no load the slip becomes very close to zero. The magnetizing inductance and core loss resistance are predominant in the motor model under these conditions because they are magnitudes larger than the leakage inductances and rotor/stator resistances.



When $S = 0$ model reduces to:

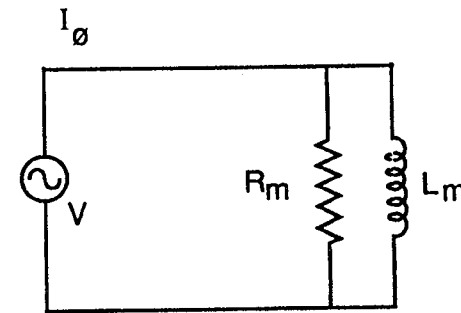


Figure 3

Appendix A, Motor Test Procedure

No Load Measurements:

- 1) Measure the Real or Effective Power and the voltage at the motor Line to Neutral terminals on a per phase basis. These measurements should be made over a range of voltages and drive frequencies. Using the data gathered in this test the core loss resistance (R_m) may be calculated. This measurement should be made with test equipment capable of reading the entire harmonic spectrum produced by the PDM controller.

$$R_m = \frac{V^2}{\text{Power}_R}$$

- 2) Magnetizing Inductance: This measurement requires that the per phase voltage and current be determined at the motor's fundamental test frequency. This is necessary because the magnetizing inductance is measured indirectly using the no load impedance and then computed from the following formulas:

A) Calculate the No Load Impedance Z_{nl} :

$$Z_{nl} = \frac{V}{I}$$

B) Calculate the magnetizing reactance (X_M) from Z_{nl} :

$$\frac{1}{X_M} = \frac{1}{Z_{nl}} - \frac{1}{R_m}$$

C) Calculate the equivalent magnetizing inductance:

$$L_m = \frac{X_M}{2 \pi F}$$

Note: The voltage and current measured in step (A) must be the motor drive fundamental frequency. With a PDM controller the fundamental frequency component of the voltage is difficult to measure because the voltage is a series of pulses. Signal filtering or signal processing is necessary to identify the magnitude of the fundamental voltage component.

APPENDIX B

Motor Parameters Test Data; GDSS and Sundstrand

The tables containing the measured data have column headings defined below:

<u>Heading</u>	<u>Definition</u>
Core Loss Resistance (Ohms)	The calculated core loss resistance of the induction motor.
Current (A) One Phase	The measured stator current amps per phase.
Current (A) Single Phase	The measured stator current amps per phase.
FREQ Hz	The stator drive frequency.
Ids (A)	The commanded value of Ids.
Impedance Single Phase (Ohms)	The impedance of the motor at its fundamental frequency.
Iqs Ids (A)	The commanded value of Iqs and Ids in amps.
Leakage Inductance (Henries)	The calculated leakage inductance of the motor in Henries.
Magnetizing Inductance (Henries)	The calculated magnetizing inductance of the induction motor in Henries.
Power (W) One Phase All Harm.	The real power into a single phase of the motor.
Power (W) Single Phase	The real power into a single phase of the motor.
Rotor Resistance (Ohms)	The calculated rotor resistance in ohms.
Stator Resistance (Ohms)	The measured stator resistance in ohms.
Temp, Mtr Deg. F	The temperature of the motor's stator in Degrees Fahrenheit.
Volts L-N All Harm.	The motor voltage from line to neutral including all harmonics.
Volts L-N Fund	The motor voltage from line to neutral of the fundamental stator drive frequency.
Volts L-N Harmonics	The motor voltage from line to neutral including all harmonics.
Volts L-N	The motor voltage from line to neutral including all harmonics.

NO LOAD 5-11-93; GDSS

V Fund. Measured w/TEK 602 Scope, Filtered Diff Amp + Avg (8) Vlink = 350									
All Harmonic V, I, Power w/Yokogawa 2533; No Load									
FREQ	Ids	TEMP, MTR	Volts	Volts	Current (A)	Power (W)	Core Loss	Impedance	Magnetizing
Hz	(A)	Degrees F	L-N	L-N	Single Phase	Single Phase	Resistance	Single Phase	Inductance
			Fund.	Harmonics			(Ohms)	(Ohms)	(Henries)
150	30	150	9.6	23	28	99	5.34E+00	3.43E-01	3.89E-04
150	40	150	12.8	27.5	36.8	163	4.64E+00	3.48E-01	3.99E-04
150	50	150	15.5	35	45.8	249	4.92E+00	3.38E-01	3.86E-04
150	60	150	18	42.7	54.9	350	5.21E+00	3.28E-01	3.71E-04
225	30	150	14.1	24.7	28.1	107	5.70E+00	5.02E-01	3.89E-04
225	40	150	18.8	31.9	37.3	188	5.41E+00	5.04E-01	3.93E-04
225	50	150	22.9	37.5	46.5	285	4.93E+00	4.92E-01	3.87E-04
225	60	150	27	47.1	55.8	390	5.69E+00	4.84E-01	3.74E-04
448	30	150	30.6	38.2	28.5	158	9.24E+00	1.07E+00	4.32E-04
448	40	150	40.6	49	37.6	267	8.99E+00	1.08E+00	4.36E-04
448	50	150	49	59.3	46.4	400	8.79E+00	1.06E+00	4.27E-04
448	60	150	56.8	69.1	55.8	553	8.63E+00	1.02E+00	4.10E-04

27

[illegible]

V Fund. Measured w/TEK 602 Scope, Filtered Diff Amp + Avg (64) Vlink = 350

All Harmonic V, I, Power w/Yokogawa 2533; Blocked Rotor

FREQ	Iqs	Temp, Mtr	Volts	Volts	Current (A)	Power (W)	Stator	Rotor	Impedance	Leakage
Hz	Ids	Deg. F	L-N	L-N	One Phase	One Phase	Resistance	Resistance	Single Phase	Inductance
	(A)		Fund.	All Harm.		All Harm.	(Ohms)	(Ohms)	(Ohms)	(Henries)
150	30	150	3.1	24.9	38.2	93.00	0.05	1.37E-02	8.12E-02	5.33E-05
150	40	150	3.8	34.6	50	164.00	0.05	1.56E-02	7.60E-02	4.07E-05
150	50	150	4.7	43.7	62.5	256.00	0.05	1.55E-02	7.52E-02	3.91E-05
150	60	150	5.8	50.9	74.2	356.00	0.05	1.47E-02	7.82E-02	4.66E-05
225	30	150	3.1	25.9	38.3	98.00	0.05	1.68E-02	8.09E-02	3.23E-05
225	40	150	4.6	35.3	50.6	171.00	0.05	1.68E-02	9.09E-02	4.36E-05
225	50	150	5.8	44.2	63	270.00	0.05	1.80E-02	9.21E-02	4.39E-05
225	60	150	6.8	51.7	74.5	367.00	0.05	1.61E-02	9.13E-02	4.45E-05
488	30	150	6.8	27.6	38.7	113.00	0.05	2.54E-02	1.76E-01	5.18E-05
488	40	150	8.9	36.3	50.9	191.00	0.05	2.37E-02	1.75E-01	5.17E-05
488	50	150	11.2	46.7	63.2	307.00	0.05	2.69E-02	1.77E-01	5.21E-05
488	60	150	13.2	53	74.4	415.00	0.05	2.50E-02	1.77E-01	5.25E-05
585	30	150	7.9	29.1	38.6	119.00	0.05	2.99E-02	2.05E-01	5.13E-05
585	40	150	10.7	37.5	51.3	206.00	0.05	2.83E-02	2.09E-01	5.26E-05

Blocked Rotor 5/93: GDSS

FREQ	Iqs	Temp, Mtr	Volts	Volts	Current (A)	Power (W)	Stator	Rotor	Impedance	Leakage
Hz	Ids	Deg. F	L-N	L-N	One Phase	One Phase	Resistance	Resistance	Single Phase	Inductance
	(A)		Fund.	All Harm.		All Harm.	(Ohms)	(Ohms)	(Ohms)	(Henries)
585	50	150	13.1	47.8	63	320.00	0.05	3.06E-02	2.08E-01	5.22E-05
585	60	150	15.5	53.2	74.9	435.00	0.05	2.75E-02	2.07E-01	5.22E-05
730	30	150	9.6	29.8	38.6	126.00	0.05	3.46E-02	2.49E-01	5.10E-05
730	40	150	12.9	38.9	50.8	216.00	0.05	3.37E-02	2.54E-01	5.23E-05
730	50	150	16	48	63	336.00	0.05	3.47E-02	2.54E-01	5.22E-05
730	60	160	19	55.8	75.3	464.00	0.051	3.08E-02	2.52E-01	5.21E-05

NO LOAD Sundstrand

FREQ	Volts	Current (A)	Power (W)	Core Loss	Impedance	Magnetizing	Power Factor
Hz	L-N	Single Phase	Single Phase	Resistance	Single Phase	Inductance	
				(Ohms)	(Ohms)	(Henries)	
This test data was supplied by Sundstrand. Testing performed with sine wave drive voltages and currents.							
166	1.48	3.67	1.43	1.53E+00	4.03E-01	5.25E-04	0.26
166	4.9	11.8	6	4.00E+00	4.15E-01	4.44E-04	0.10
166	10.07	24.4	21.7	4.67E+00	4.13E-01	4.34E-04	0.09
166	19.74	49.92	78.3	4.98E+00	3.95E-01	4.12E-04	0.08
166	30.54	105.2	292	3.19E+00	2.90E-01	3.06E-04	0.09
500	4.19	3.72	4.4	3.99E+00	1.13E+00	5.00E-04	0.28
500	10.59	8.61	10	1.12E+01	1.23E+00	4.40E-04	0.11
500	30.13	24.2	47	1.93E+01	1.25E+00	4.24E-04	0.06
500	50.58	41.74	120	2.13E+01	1.21E+00	4.09E-04	0.06
500	71.99	59.52	220	2.36E+01	1.21E+00	4.06E-04	0.05
500	90.74	98.89	450	1.83E+01	9.18E-01	3.08E-04	0.05
750	4.15	3.59	3.33	5.17E+00	1.16E+00	3.16E-04	0.22
750	14.5	8.04	18	1.17E+01	1.80E+00	4.53E-04	0.15
750	23.3	12.7	31	1.75E+01	1.83E+00	4.35E-04	0.10
750	40.88	22.29	72	2.32E+01	1.83E+00	4.23E-04	0.08

NO LOAD, strand

FREQ	Volts	Current (A)	Power (W)	Core Loss	Impedance	Magnetizing	Power Factor
Hz	L-N	Single Phase	Single Phase	Resistance	Single Phase	Inductance	
				(Ohms)	(Ohms)	(Henries)	
750	79.8	45.14	213	2.99E+01	1.77E+00	3.99E-04	0.06
750	121.3	78.25	463	3.18E+01	1.55E+00	3.46E-04	0.05
750	130.7	87.53	540	3.16E+01	1.49E+00	3.33E-04	0.05

BLOCKED ROTOR - Sundstrand

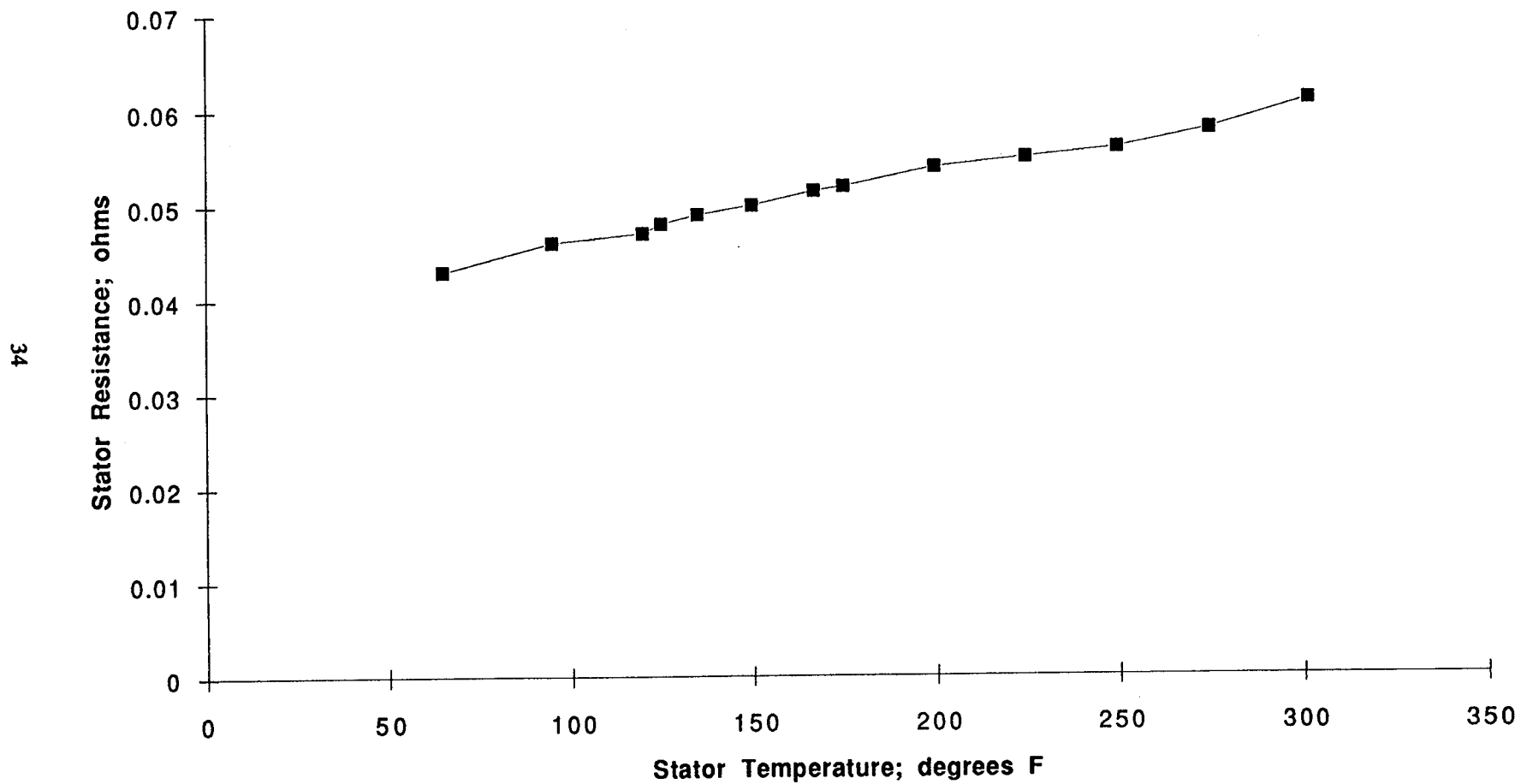
FREQ	Volts	Current (A)	Power (W)	Stator	Rotor	Impedance	Leakage	Power Factor
Hz	L-N	Single Phase	Single Phase	Resistance	Resistance	Single Phase	Inductance	
				(Ohms)	(Ohms)	(Ohms)	(Henries)	
This test data was supplied by Sundstrand. Testing performed with sine wave drive voltages and currents								
50	2.19	30.45	38.3	0.016	2.53E-02	7.19E-02	1.88E-04	0.57
50	5.22	74.15	228	0.016	2.55E-02	7.04E-02	1.81E-04	0.59
50	7.65	108.8	499	0.016	2.62E-02	7.03E-02	1.79E-04	0.60
50	9.83	131.8	787	0.016	2.93E-02	7.46E-02	1.89E-04	0.61
500	3.21	17.3	15	0.016	3.41E-02	1.86E-01	5.69E-05	0.27
500	4.86	26.55	35	0.016	3.37E-02	1.83E-01	5.61E-05	0.27
500	15.14	83.6	355	0.016	3.48E-02	1.81E-01	5.54E-05	0.28
500	25.35	135	1000	0.016	3.89E-02	1.88E-01	5.72E-05	0.29
750	4.04	15.79	12.7	0.016	3.49E-02	2.56E-01	5.32E-05	0.20
750	9.84	39.15	77	0.016	3.42E-02	2.51E-01	5.23E-05	0.20
750	14.79	58.88	177	0.016	3.51E-02	2.51E-01	5.22E-05	0.20
750	24.7	97.44	506	0.016	3.73E-02	2.53E-01	5.26E-05	0.21
750	34.76	133.43	1057	0.016	4.34E-02	2.61E-01	5.39E-05	0.23

Stator Temp vs Rs #2

Temperature <i>Degrees F</i>	Stator Resistance <i>Ohms L-N</i>
65	0.043
95	0.046
120	0.047
125	0.048
135	0.049
150	0.05
167	0.0515
175	0.052
200	0.054
225	0.055
250	0.056
275	0.058
302	0.061

Stator Resistance vs Temp #2

Stator Resistance vs Temperature

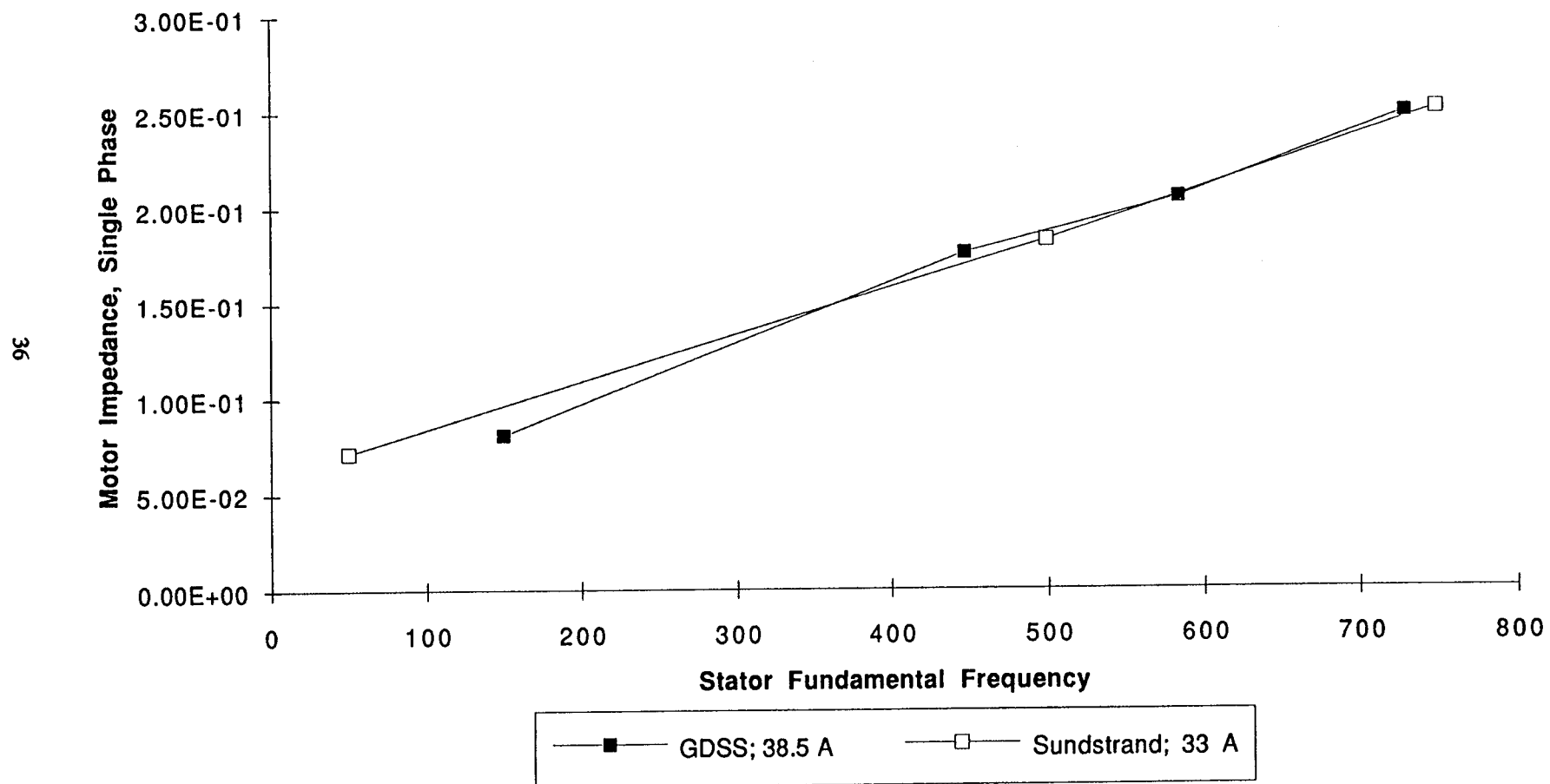


APPENDIX C

Motor Impedance Comparison; GDSS and Sundstrand

Motor 2, 35 A

Blocked Rotor Impedance



APPENDIX D

Gear Box Friction Calibration Data

<u>Heading</u>	<u>Definition</u>
Average Torque in-lbs	The average torque required to overcome the gearbox friction with the oil pump on, measured in in-lbs.
Dyno Speed RPM	The speed of the dynamometer shaft .
Dyno Torque in-lbs Before Cal	The torque required to overcome the gearbox friction with the oil pump on, measured in in-lbs prior to re-calibration.
Dyno Torque in-lbs Pump On	The torque required to overcome the gearbox friction with the oil pump on, measured in in-lbs.
Standard Deviation	The standard deviation of the friction torque measurements.
Temp of Oil (Deg.F)	The temperature of the oil in the gearbox.
Time Minutes	The elapsed time from the beginning of the test.

Gear Box Friction Test Notes

July 1993

- All temperature measurements were made with Doric 412A Temperature Meter.
- "Dyno Torque in-lbs, Pump On" is the gearbox frictional losses with the oil pump in the on condition.
- "Dyno Torque in-lbs, Before Cal" is the gearbox frictional losses prior to calibrating the dynamometer.
- "Time Minutes" is the elapsed time from when the dynamometer was turned on.
- The oil temperature sensor was mounted on the oil outflow pipe of the gearbox.
- This information was used to adjust previous torque data gathered on the dynamometer to include the gearbox frictional losses.

Gear Reducer vs Temp

Dyno	Temp.	Dyno	Average	Standard	Time	Dyno
Speed	of	Torque	Torque	Deviation	Minutes	Torque
RPM	Oil	in-lbs	in-lbs			in-lbs
	(Deg. F)	Pump On				Before Cal
700	70.4	29			0	24
700	78	19			5	14
700	83	18			7	13
700	84.8	17			8	12
700	86.6	16			10	11
700	95	15			15	10
700	96	14			17	9
700	103	12			25	7
700	110.6	10			38	5
700	114.8	9			50	4
700	118.6	7	15.1	5.7	65	2
1450	70.4	36			0	31
1450	78.8	29			5	24
1450	83.7	28			7	23
1450	85.5	27			8	22
1450	87.7	26			10	21
1450	95.2	24			15	19
1450	96.2	23			17	18
1450	103	21			25	16
1450	110.6	18			38	13
1450	114	15			50	10
1450	117.6	14	22.3	6.2	65	9
2200	70.8	39			0	34
2200	79.3	35			5	30
2200	83.7	32			7	27
2200	85.6	31			8	26
2200	87.5	31			10	26
2200	94	29			15	24
2200	95.8	28			17	23
2200	102	25			25	20
2200	109	23			38	18
2200	113	21			50	16
2200	117.3	19	28.5	5.8	65	14
2950	71	43			0	38
2950	79.6	37			5	32
2950	83.6	35			7	30
2950	85.4	35			8	30
2950	87.3	35			10	30
2950	93.4	33			15	28
2950	94.8	32			17	27
2950	100.4	29			25	24

Gear Reducer vs Temp

2950	107	27			38	22
2950	113	25			50	20
2950	115.5	23	32.2	6.8	65	18
3450	71.7	45			0	40
3450	80	40			5	35
3450	84	38			7	33
3450	86	37			8	32
3450	87.6	37			10	32
3450	93.7	36			15	31
3450	95	35			17	30
3450	102	32			25	27
3450	109.8	30			38	25
3450	114	28			50	23
3450	117.8	26	34.9	5.3	65	21

APPENDIX E

Motor Curves Test Data and Charts

The tables containing the measured data have column headings defined below:

<u>Heading</u>	<u>Definition</u>
Dyno HP	The horsepower out of the motor, adjusted for gearbox inefficiencies.
Dyno Speed RPM	The speed of the dynamometer shaft.
fs-fr FREQ, Hz	The difference between the stator and rotor frequencies.
Ks	The slip constant used in computing the commanded motor slip.
Motor Current (A/phase)	The measured stator current amps per phase.
Motor Eff.	The efficiency of the motor. Calculated by dividing the power out of the motor by the power into the motor.
Motor Power (W) 1 Phase	The real power in one phase of the motor.
Motor Speed RPM	The speed of the induction motor's shaft in revolutions per minute.
Motor Temp deg F	The temperature of the stator in degrees Fahrenheit.
Motor Torque in-lbs	The motor torque output at the motor shaft.
Motor Volts L-N Harmonics	The motor voltage measured line to neutral
PF	The power factor of the power into the motor.
Slip %	The % difference between the rotating stator field and the rotor's rotational speed.
Stator FREQ, Hz	The stator current drive frequency. with all harmonics represented in the value.

Motor Curves Test Notes

July 1993

- Tested as per "40 HP Task Order System Test Plan" for contract NAS3-25799.
- All measurements were made with the 20 KHz link = 350 VAC.
- Motor currents listed on the graphs are the average per phase values for a given curve.
- All measurements made with a 200 uH choke per phase in the motor circuit unless otherwise noted.
- For each set of measurements, the system was tested at 4 stator current levels. These levels are roughly 37 A, 48 A, 60 A and 70 A per phase.
- For all measurements $I_{qs} = I_{ds}$.
- The test method maintained the stator drive frequency a constant value while varying the rotor speed.
- The measured voltage and current values are all harmonic measurements. Measurements were performed on a Yokogawa 2533 digital power meter.
- Motor torque measurements are adjusted to compensate for gear reducer gearbox friction. The gearbox friction losses decrease with rising temperature and increase at greater speeds. See "Gear Reducer vs Temp" data.

3K RPM, 40.0, 5-24-93

Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		in-lbs			deg F	RPM
				Harmonics									
150	148	740	1.33%	28.9	37.7	0.23	250	0.29	6.25	0.292	0.07	115	2960
150	146	730	2.67%	28.8	37.5	0.28	303	0.58	12.5	0.475	0.07	115	2920
150	144	720	4.00%	28.8	37.7	0.29	306	0.67	14.75	0.548	0.07	117	2880
150	142	710	5.33%	27.8	37.7	0.28	288	0.66	14.75	0.574	0.07	118	2840
150	140	700	6.67%	27.7	37.5	0.26	272	0.63	14.25	0.579	0.07	119	2800
150	136	680	9.33%	27.7	37.5	0.23	232	0.51	11.75	0.544	0.1	120	2720
150	130	650	13.33%	27.7	37.7	0.2	200	0.41	10	0.513	0.15	120	2600
150	120	600	20.00%	26.8	37.9	0.16	159	0.28	7.25	0.432	0.2	121	2400
150	110	550	26.67%	26.7	37.7	0.14	139	0.19	5.5	0.343	0.26	121	2200
150	100	500	33.33%	26.5	37.7	0.12	124	0.14	4.5	0.286	0.33	122	2000

3K RPM, 50., 5-24-93

Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		In-lbs			deg F	RPM
				Harmonics									
150	148	740	1.33%	39.66	50	0.19	391	0.39	8.25	0.246	0.07	145	2960
150	146	730	2.67%	39.6	49.7	0.25	485	0.82	17.75	0.422	0.07	145	2920
150	144	720	4.00%	39.1	49.4	0.27	529	1.09	23.75	0.510	0.07	143	2880
150	142	710	5.33%	38.8	49.3	0.28	539	1.21	26.75	0.556	0.07	141	2840
150	140	700	6.67%	38.6	49.5	0.27	514	1.20	27	0.580	0.08	140	2800
150	136	680	9.33%	38	49.9	0.23	436	0.99	23	0.566	0.1	136	2720
150	130	650	13.33%	37	50	0.2	364	0.76	18.5	0.521	0.14	135	2600
150	120	600	20.00%	36	50.5	0.16	296	0.52	13.75	0.440	0.2	134	2400
150	110	550	26.67%	36	50.5	0.14	251	0.36	10.25	0.354	0.27	130	2200
150	100	500	33.33%	35.4	50.6	0.13	223	0.27	8.5	0.301	0.33	125	2000

3K RPM, 60%, 5-26-93

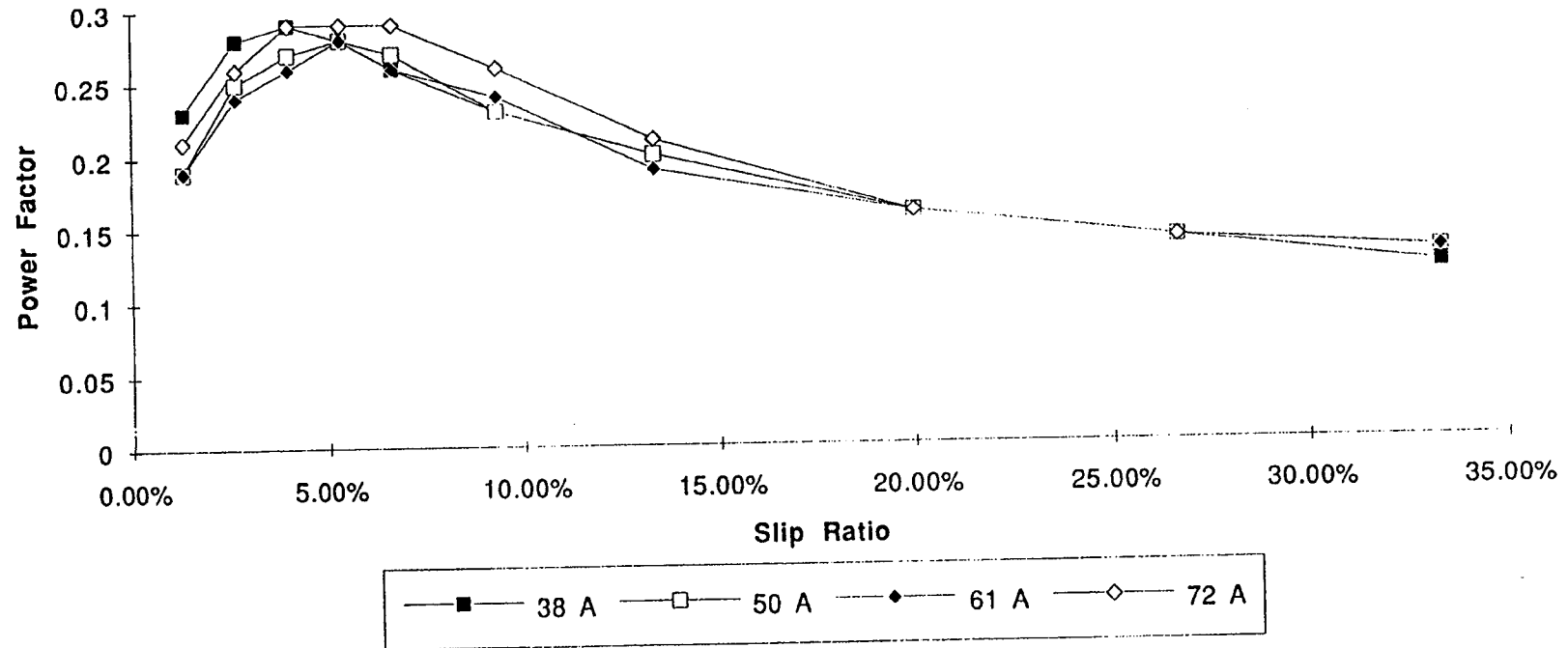
Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		In-lbs			deg F	RPM
				Harmonics									
150	148	740	1.33%	46.6	61.7	0.19	553	0.35	7.5	0.158	0.07	115	2960
150	146	730	2.67%	46.4	61.2	0.24	677	0.96	20.75	0.353	0.07	120	2920
150	144	720	4.00%	46.4	60.7	0.26	745	1.36	29.75	0.454	0.07	123	2880
150	142	710	5.33%	46.6	59.9	0.28	782	1.60	35.5	0.509	0.07	115	2840
150	140	700	6.67%	46.4	59.5	0.26	728	1.67	37.5	0.569	0.1	120	2800
150	136	680	9.33%	45.3	59.9	0.24	642	1.45	33.5	0.560	0.1	125	2720
150	130	650	13.33%	46	60.6	0.19	532	1.08	26.25	0.506	0.14	130	2600
150	120	600	20.00%	46	61.3	0.16	451	0.77	20.25	0.425	0.2	132	2400
150	110	550	26.67%	45.6	61.6	0.14	392	0.56	16	0.354	0.27	135	2200
150	100	500	33.33%	45.1	61.9	0.13	355	0.41	13	0.289	0.34	136	2000

3K RPM, 70%, 5-26-93

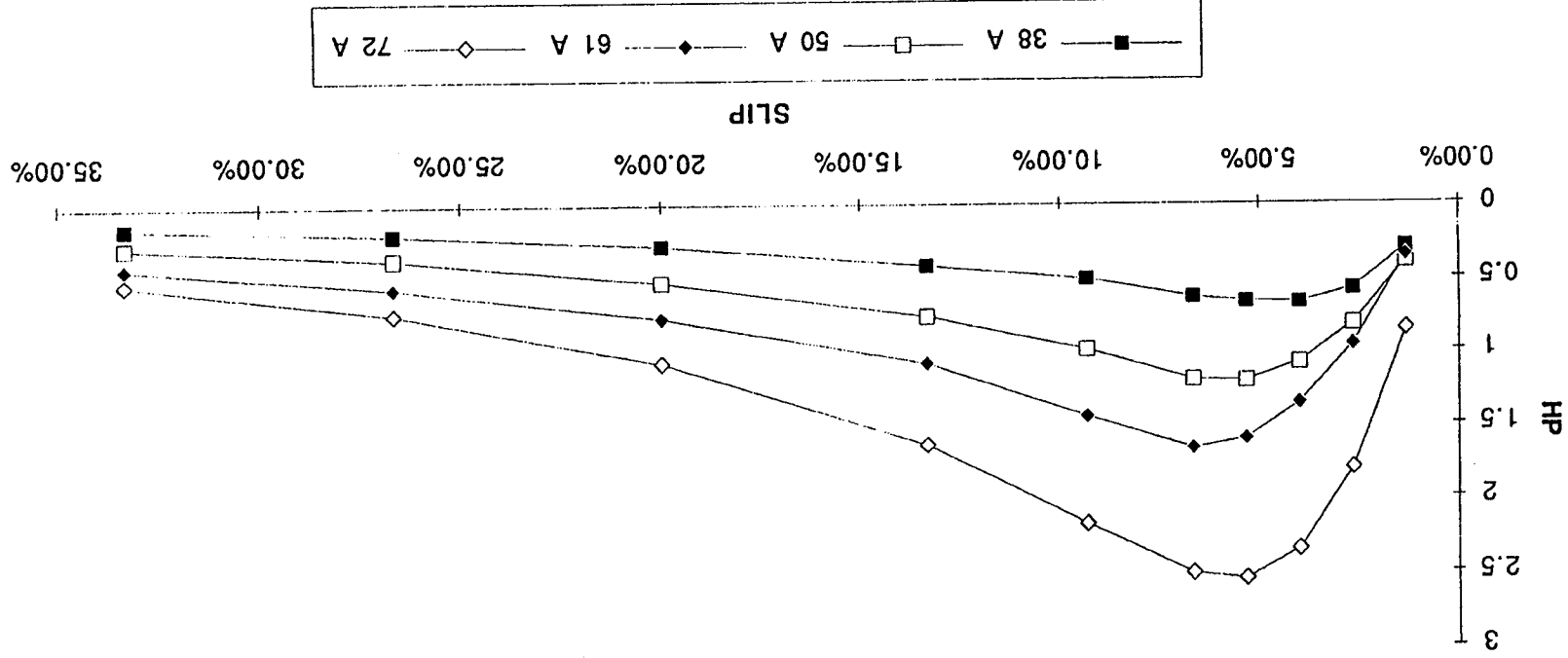
Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		in-lbs			deg F	RPM
				Harmonics									
150	148	740	1.33%	55.1	72.4	0.21	820	0.86	18.25	0.260	0.13	173	2960
150	146	730	2.67%	54.3	71.7	0.26	1020	1.81	39	0.441	0.13	170	2920
150	144	720	4.00%	53.9	71.3	0.29	1110	2.35	51.5	0.527	0.13	170	2880
150	142	710	5.33%	53.1	71.2	0.29	1110	2.55	56.5	0.570	0.13	168	2840
150	140	700	6.67%	52.8	71	0.29	1070	2.51	56.5	0.583	0.13	164	2800
150	136	680	9.33%	52	71.1	0.26	940	2.18	50.5	0.577	0.13	159	2720
150	130	650	13.33%	51	71.1	0.21	770	1.64	39.75	0.530	0.14	150	2600
150	120	600	20.00%	52.5	71.5	0.16	610	1.08	28.25	0.439	0.2	142	2400
150	110	550	26.67%	52.9	72.2	0.14	520	0.74	21.25	0.355	0.27	134	2200
150	100	500	33.33%	53.1	72.8	0.12	460	0.52	16.5	0.283	0.34	118	2000

PF/Slip 150 Hz

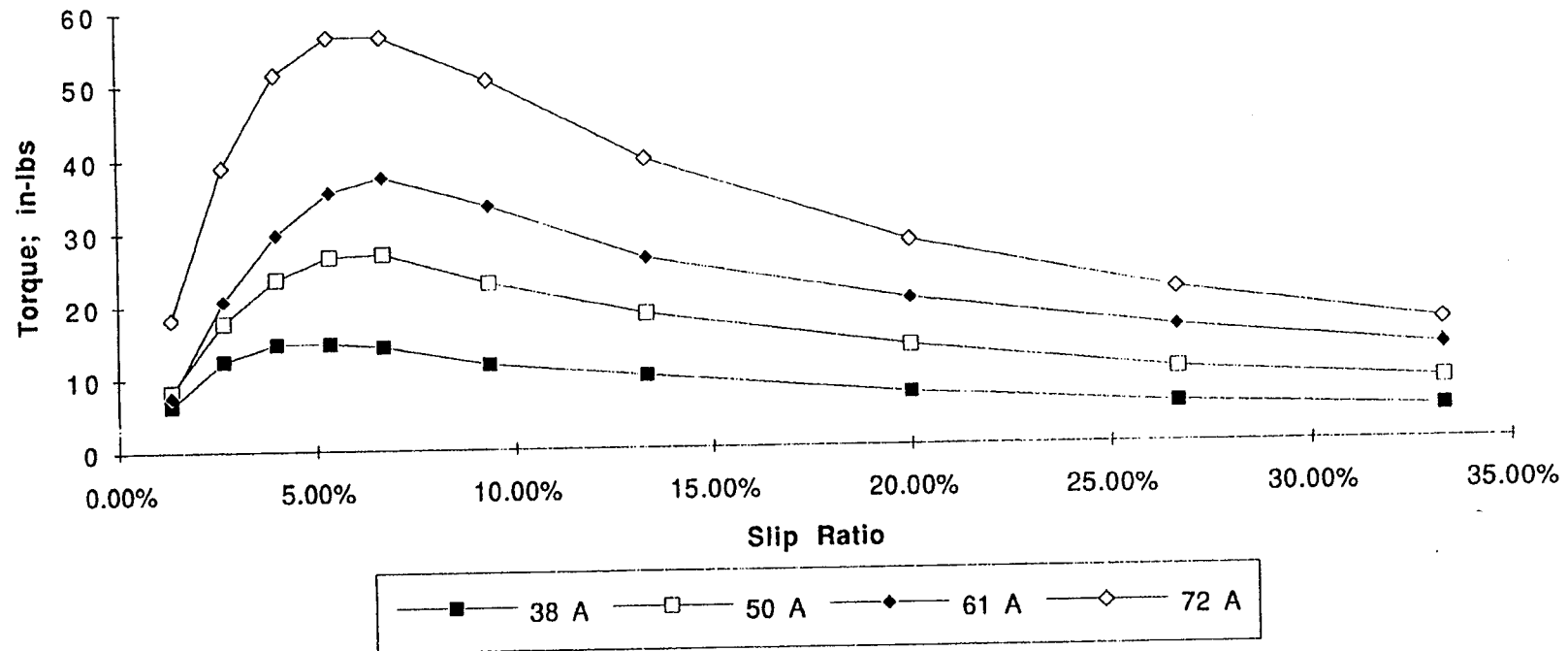
PF/Slip vs Current ($I_{ds}=I_{qs}$); Stator = 150 Hz (3000 RPM)



HP/SLIP vs Current ($I_{ds}=I_{qs}$): Stator = 150 Hz (3000 RPM)

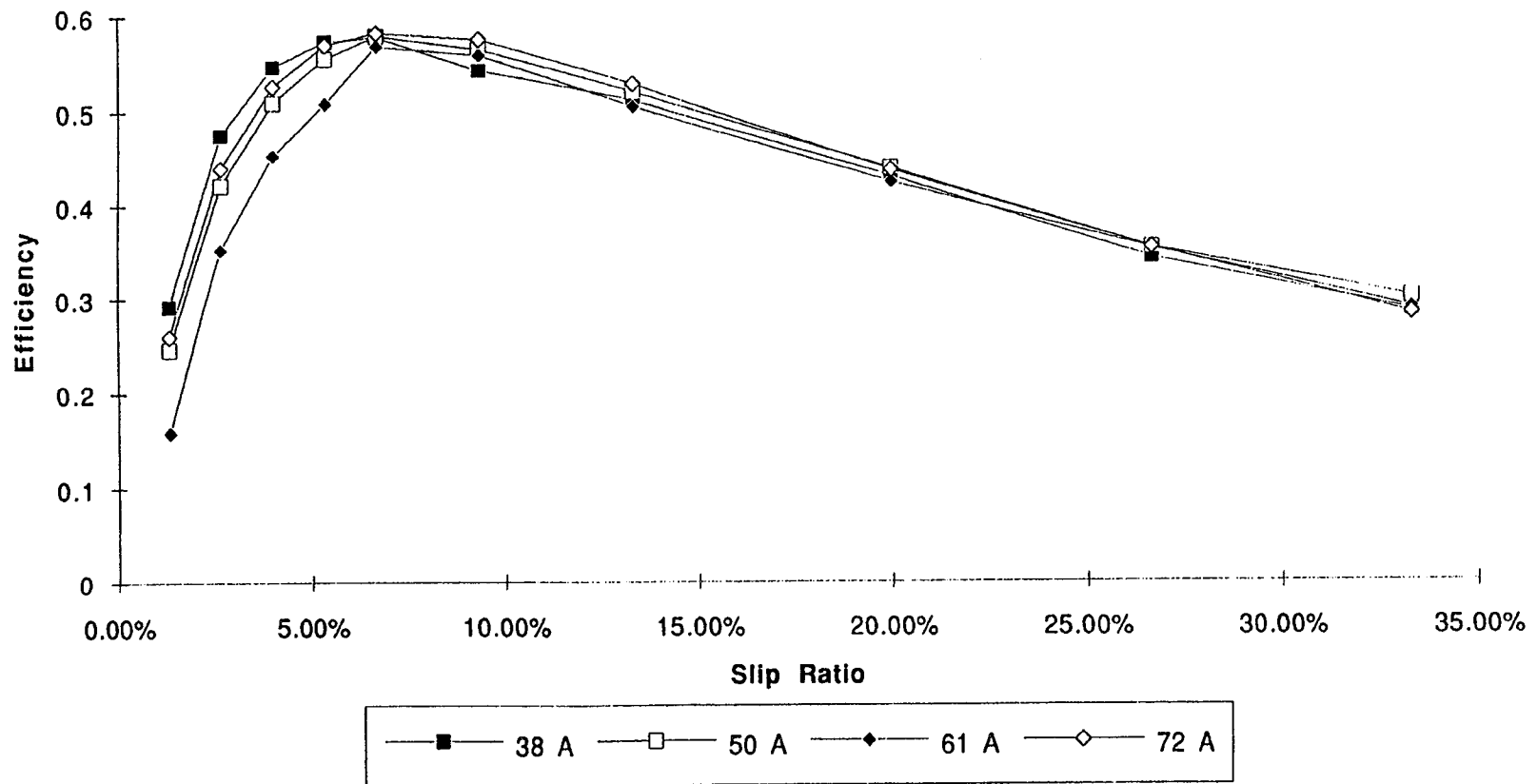


Motor Torque/Slip vs Current ($I_{ds}=I_{qs}$); Stator = 150 Hz (3000 RPM)



Eff/Slip 150 Hz

Efficiency/Slip vs Current ($I_{ds}=I_{qs}$); Stator = 150 Hz (3000 RPM)



6K RPM, 40A, 5-27-93

Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		in-lbs			deg F	RPM
				Harmonics									
300	298	1490	0.67%	37.2	37.8	0.29	415	0.64	6.75	0.382	0.1	136	5960
300	296	1480	1.33%	34.6	37.3	0.4	520	1.15	12.25	0.550	0.1	136	5920
300	294	1470	2.00%	33.4	37.2	0.42	518	1.21	13	0.582	0.08	134	5880
300	292	1460	2.67%	32.7	37.2	0.4	490	1.16	12.5	0.588	0.08	138	5840
300	290	1450	3.33%	31.4	37.2	0.39	453	1.13	12.25	0.619	0.08	141	5800
300	288	1440	4.00%	31	37	0.37	423	1.05	11.5	0.618	0.09	143	5760
300	286	1430	4.67%	31	36.9	0.37	423	1.04	11.5	0.614	0.09	143	5720
300	284	1420	5.33%	31	37.3	0.35	406	0.99	11	0.607	0.1	145	5680
300	280	1400	6.67%	30.2	37.6	0.31	355	0.82	9.25	0.576	0.13	145	5600
300	260	1300	13.33%	28.5	37.9	0.21	222	0.37	4.5	0.416	0.27	146	5200
300	240	1200	20.00%	28	38	0.16	175	0.21	2.75	0.298	0.41	145	4800

6K RPM, 50A, 5-27-93

Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		In-lbs			deg F	RPM
				Harmonics									
300	298	1490	0.67%	48.9	50.3	0.23	547	0.35	3.75	0.161	0.07	126	5960
300	296	1480	1.33%	47.3	50	0.33	753	1.34	14.25	0.442	0.07	123	5920
300	294	1470	2.00%	44.7	49.3	0.4	858	1.87	20	0.541	0.07	122	5880
300	292	1460	2.67%	43.4	49.3	0.42	870	2.06	22.25	0.589	0.07	121	5840
300	290	1450	3.33%	42	49	0.42	840	2.05	22.25	0.606	0.07	119	5800
300	288	1440	4.00%	41	49	0.4	797	1.96	21.5	0.613	0.07	118	5760
300	286	1430	4.67%	39.6	49.2	0.37	705	1.70	18.75	0.600	0.09	118	5720
300	284	1420	5.33%	39.6	49.3	0.35	666	1.60	17.75	0.597	0.1	120	5680
300	280	1400	6.67%	39.6	49.5	0.3	579	1.33	15	0.572	0.13	121	5600
300	260	1300	13.33%	37.6	50.4	0.2	374	0.62	7.5	0.411	0.27	121	5200
300	240	1200	20.00%	36.8	50.9	0.16	300	0.32	4.25	0.268	0.41	120	4800
300	220	1100	26.67%	37.4	51.3	0.14	264	0.21	3	0.197	0.53	120	4400

6K RPM, 60n, 5-27-93

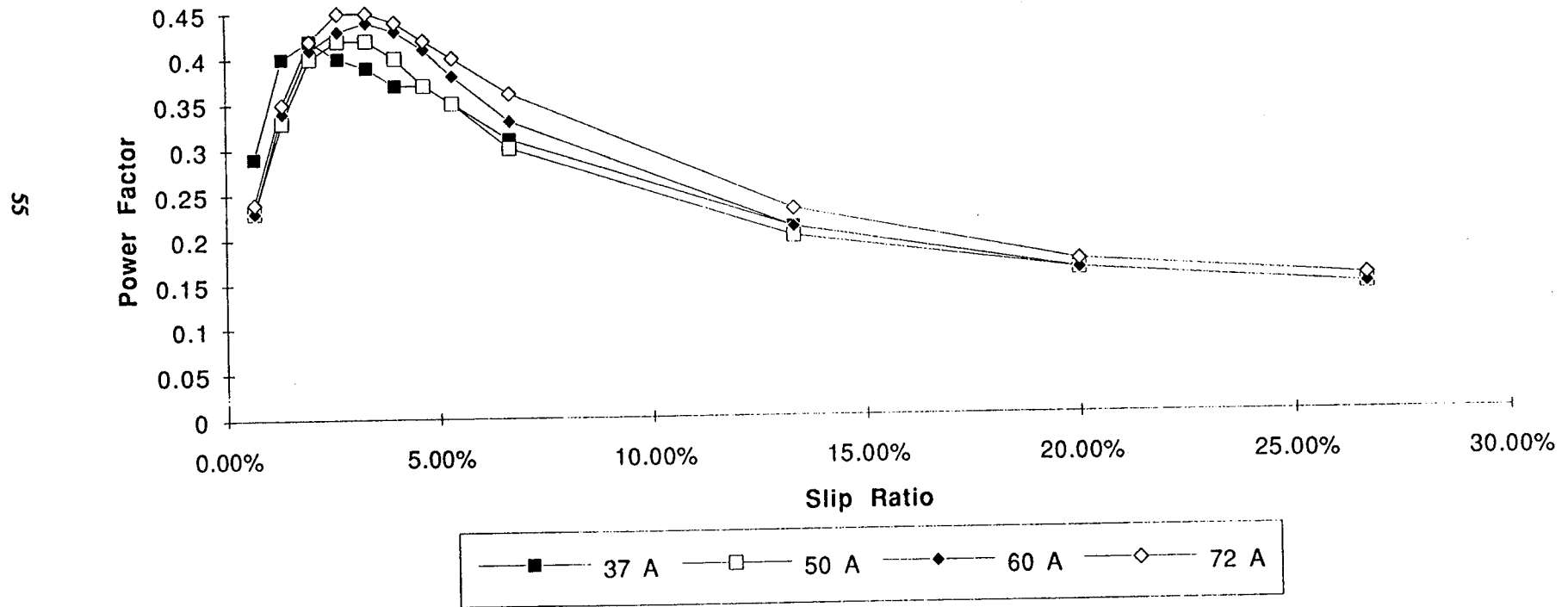
Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		in-lbs			deg F	RPM
				Harmonics									
300	298	1490	0.67%	58	61.1	0.23	821	0.87	9.25	0.265	0.1	146	5960
300	296	1480	1.33%	56	60.1	0.34	1135	2.25	24	0.494	0.1	145	5920
300	294	1470	2.00%	53.2	59.7	0.41	1297	3.13	33.5	0.599	0.1	143	5880
300	292	1460	2.67%	51.4	59.7	0.43	1322	3.38	36.5	0.636	0.1	142	5840
300	290	1450	3.33%	49.6	60.1	0.44	1294	3.41	37	0.654	0.1	141	5800
300	288	1440	4.00%	47.9	60.4	0.43	1228	3.29	36	0.666	0.1	140	5760
300	286	1430	4.67%	47.3	60.4	0.41	1166	3.11	34.25	0.663	0.1	139	5720
300	284	1420	5.33%	47.2	60.4	0.38	1093	2.86	31.75	0.651	0.1	137	5680
300	280	1400	6.67%	46.2	60.6	0.33	932	2.33	26.25	0.622	0.13	135	5600
300	260	1300	13.33%	46.1	61.5	0.21	591	1.11	13.5	0.469	0.27	133	5200
300	240	1200	20.00%	46	62.4	0.16	468	0.63	8.25	0.334	0.41	130	4800
300	220	1100	26.67%	43.3	62.5	0.14	405	0.42	6	0.257	0.41	127	4400

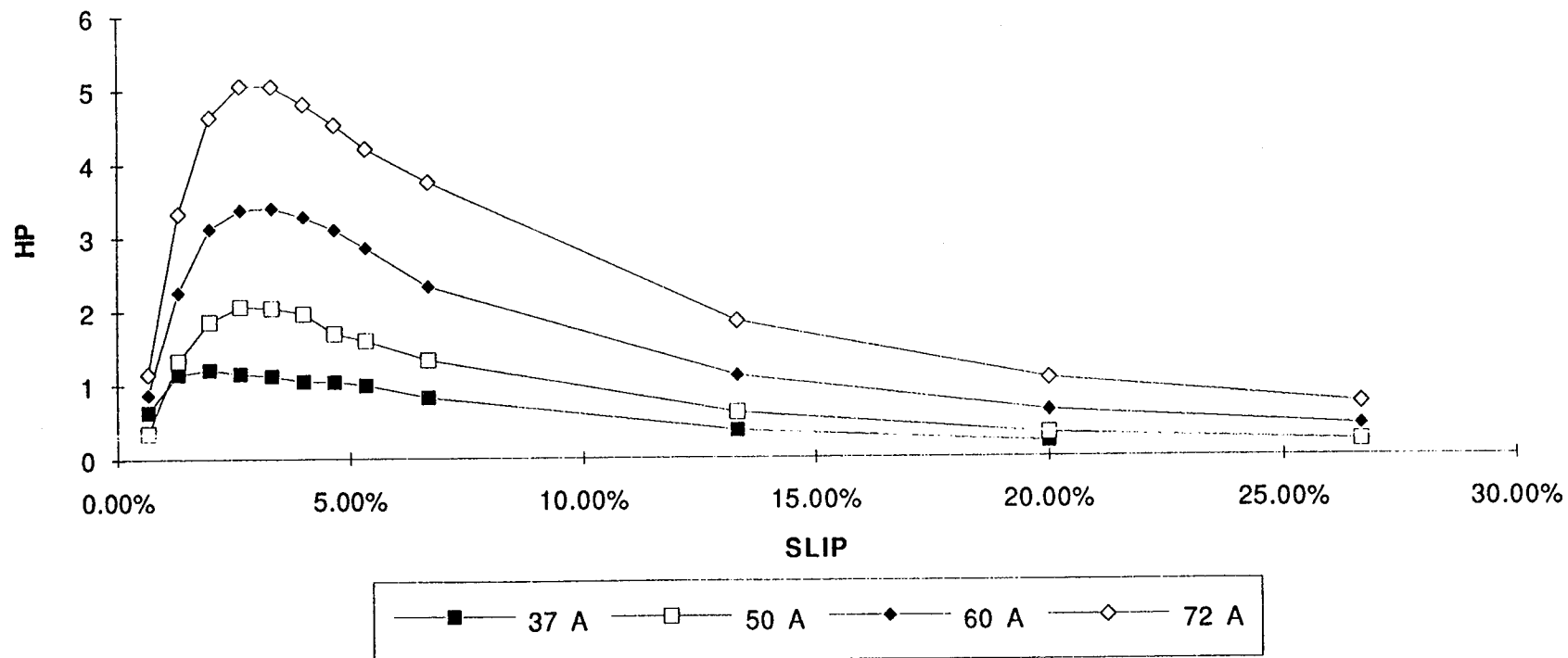
6K RPM, 70M; 5-27-93

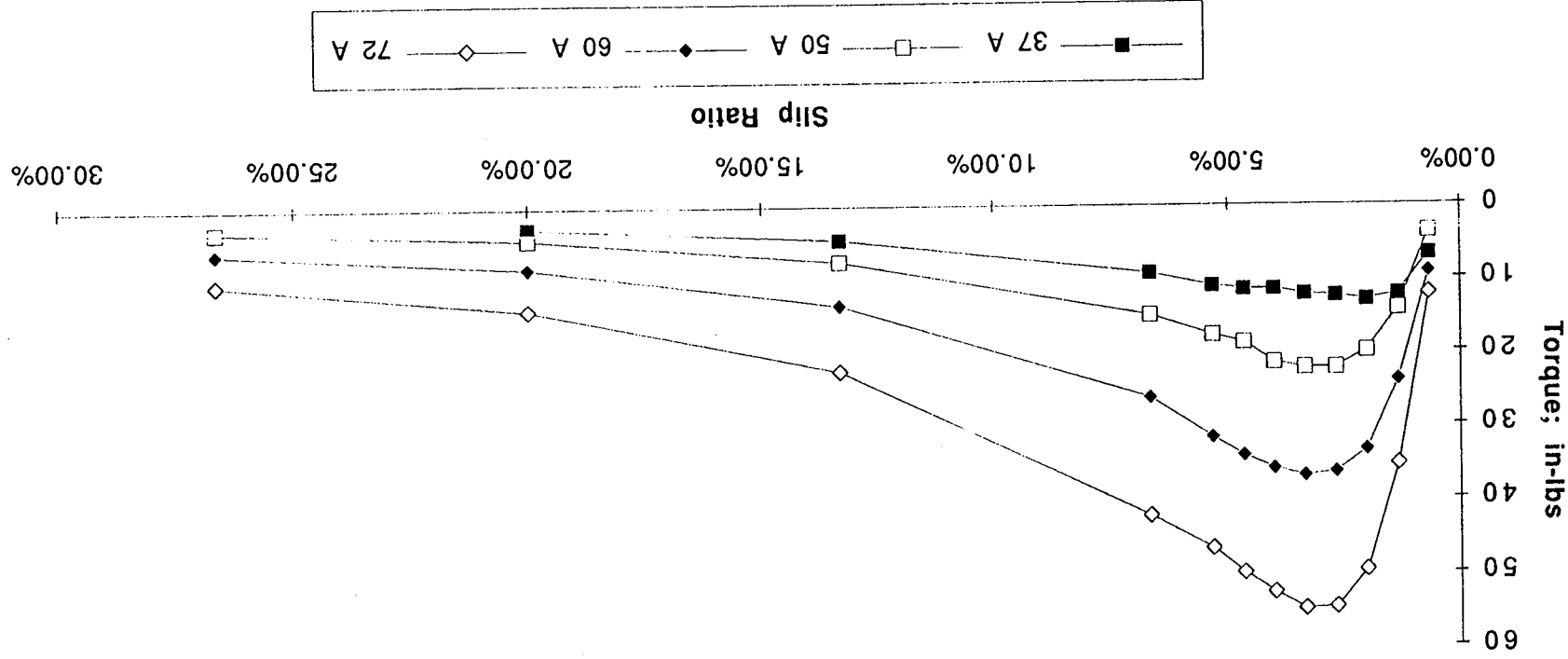
Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		In-lbs			deg F	RPM
				Harmonics									
300	298	1490	0.67%	67.3	73	0.24	1155	1.16	12.25	0.249	0.13	176	5960
300	296	1480	1.33%	64.7	72	0.35	1620	3.33	35.5	0.512	0.13	173	5920
300	294	1470	2.00%	62	71.6	0.42	1871	4.64	49.75	0.617	0.13	171	5880
300	292	1460	2.67%	59.5	71.3	0.45	1912	5.07	54.75	0.660	0.13	169	5840
300	290	1450	3.33%	57.8	71.3	0.45	1851	5.06	55	0.680	0.13	168	5800
300	288	1440	4.00%	56.3	71.2	0.44	1750	4.82	52.75	0.685	0.13	166	5760
300	286	1430	4.67%	55	71.7	0.42	1655	4.54	50	0.682	0.13	164	5720
300	284	1420	5.33%	53.9	71.9	0.4	1550	4.21	46.75	0.676	0.13	160	5680
300	280	1400	6.67%	52.9	72.2	0.36	1395	3.75	42.25	0.669	0.13	156	5600
300	260	1300	13.33%	53.1	73.3	0.23	873	1.86	22.5	0.529	0.27	154	5200
300	240	1200	20.00%	52.3	73.6	0.17	667	1.07	14	0.398	0.41	151	4800
300	220	1100	26.67%	52.7	73.6	0.15	569	0.72	10.25	0.313	0.53	146	4400

PF/Slip 300 Hz

PF/Slip vs Current ($I_{ds}=I_{qs}$); Stator = 300 Hz (6000 RPM)



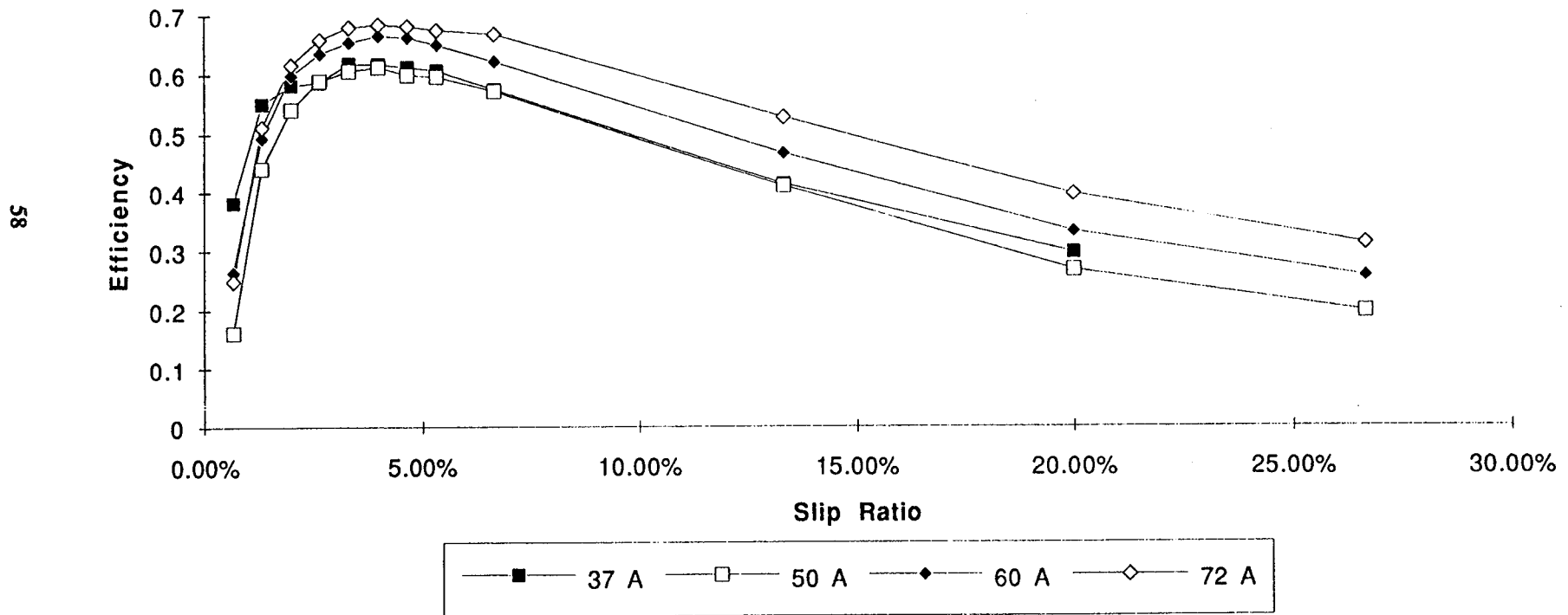
HP/SLIP vs Current ($I_{ds}=I_{qs}$); Stator = 300 Hz (6000 RPM)



Torque/Slip 300 Hz

Eff/Slip 300 Hz

Efficiency/Slip vs Current ($I_{ds}=I_{qs}$); Stator = 300 Hz (6000 RPM)



9K RPM, 40A; 5-28-93

Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		in-lbs			deg F	RPM
				Harmonics									
450	447	2235	0.67%	45.7	37.1	0.33	561	1.28	9	0.566	0.07	146	8940
450	446	2230	0.89%	44.6	36.9	0.38	628	1.59	11.25	0.630	0.07	145	8920
450	444	2220	1.33%	40.7	36.6	0.47	704	2.11	15	0.747	0.07	143	8880
450	442	2210	1.78%	37.5	36.8	0.51	707	2.21	15.75	0.777	0.07	142	8840
450	440	2200	2.22%	36	36.9	0.51	674	2.13	15.25	0.786	0.07	142	8800
450	438	2190	2.67%	34.5	37	0.5	636	2.02	14.5	0.788	0.08	141	8760
450	434	2170	3.56%	32.6	37.2	0.44	540	1.72	12.5	0.793	0.11	140	8680
450	430	2150	4.44%	31.5	37	0.41	485	1.54	11.25	0.787	0.13	141	8600
450	420	2100	6.67%	30.6	37.7	0.32	370	1.07	8	0.717	0.2	142	8400

9K RPM, 50.0; 5-28-93

Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		in-lbs			deg F	RPM
				Harmonics									
450	447	2235	0.67%	58.4	49.2	0.29	836	1.70	12	0.506	0.07	148	8940
450	446	2230	0.89%	56.9	48.6	0.34	940	2.19	15.5	0.580	0.07	147	8920
450	444	2220	1.33%	52.5	48	0.46	1160	3.24	23	0.695	0.08	143	8880
450	442	2210	1.78%	47.4	48	0.52	1173	3.51	25	0.743	0.09	140	8840
450	440	2200	2.22%	45.5	48.4	0.52	1132	3.49	25	0.767	0.09	141	8800
450	438	2190	2.67%	43.3	48.4	0.5	1056	3.23	23.25	0.761	0.09	142	8760
450	434	2170	3.56%	40.7	49.2	0.46	926	2.82	20.5	0.758	0.11	144	8680
450	430	2150	4.44%	40.1	49	0.42	834	2.52	18.5	0.753	0.13	145	8600
450	420	2100	6.67%	39.5	49	0.32	627	1.77	13.25	0.700	0.2	147	8400
450	400	2000	11.11%	38.8	50.3	0.24	462	1.14	9	0.615	0.33	147	8000
450	380	1900	15.56%	38	50.4	0.19	374	0.78	6.5	0.521	0.47	148	7600

9K RPM, 60A; 5-28-93

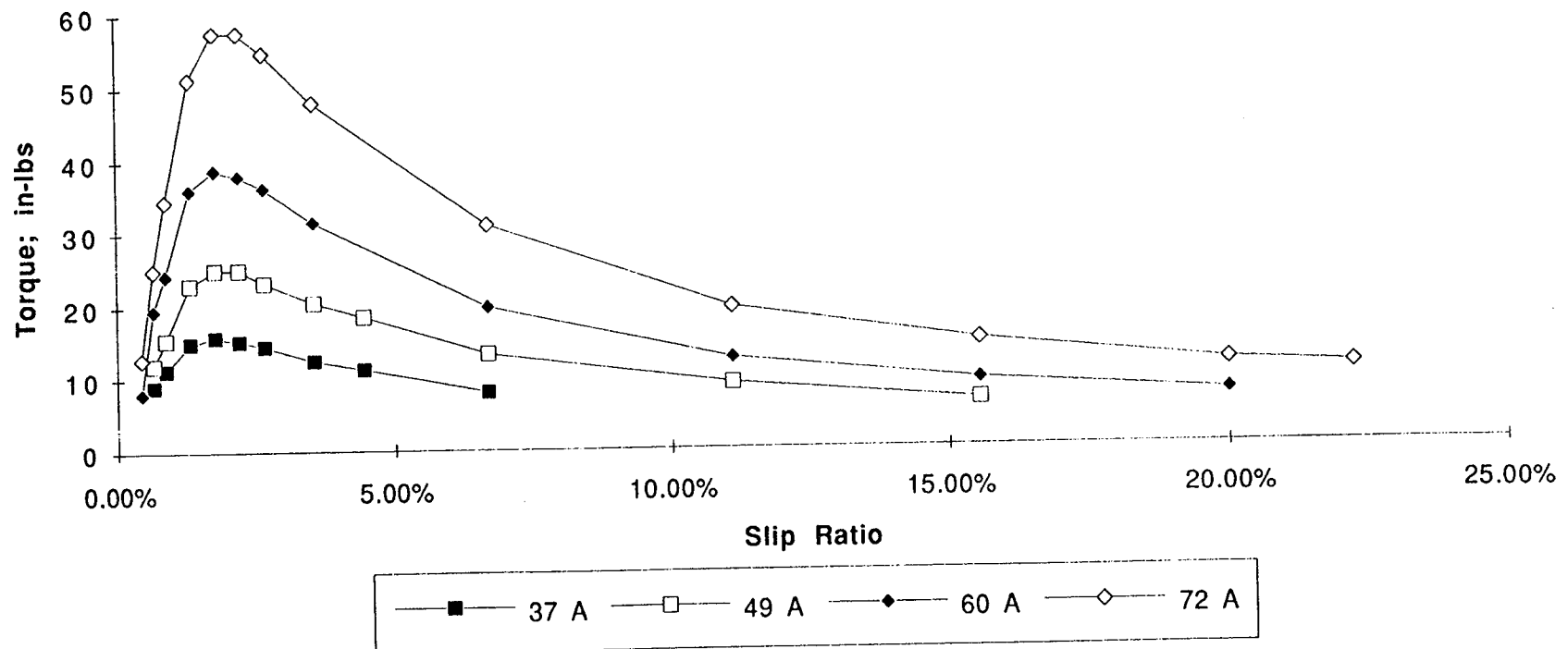
Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		in-lbs			deg F	RPM
				Harmonics									
450	448	2240	0.44%	73.9	61	0.22	980	1.14	8	0.289	0.09	168	8960
450	447	2235	0.67%	72.2	60.3	0.31	1315	2.77	19.5	0.523	0.11	174	8940
450	446	2230	0.89%	70.5	60.1	0.36	1521	3.43	24.25	0.561	0.11	175	8920
450	444	2220	1.33%	65.6	59.5	0.46	1790	5.07	36	0.705	0.11	174	8880
450	442	2210	1.78%	60.1	58.9	0.52	1835	5.44	38.75	0.737	0.11	172	8840
450	440	2200	2.22%	56.8	59.1	0.52	1760	5.31	38	0.750	0.11	168	8800
450	438	2190	2.67%	54.3	59.3	0.51	1655	5.04	36.25	0.757	0.11	165	8760
450	434	2170	3.56%	51.3	59.8	0.47	1450	4.34	31.5	0.744	0.11	163	8680
450	420	2100	6.67%	48.4	60.6	0.34	977	2.63	19.75	0.670	0.2	158	8400
450	400	2000	11.11%	47.8	61.6	0.24	694	1.59	12.5	0.569	0.34	155	8000
450	380	1900	15.56%	47.7	62.2	0.19	570	1.12	9.25	0.487	0.47	153	7600
450	360	1800	20.00%	47.2	62.3	0.17	496	0.83	7.25	0.415	0.61	152	7600

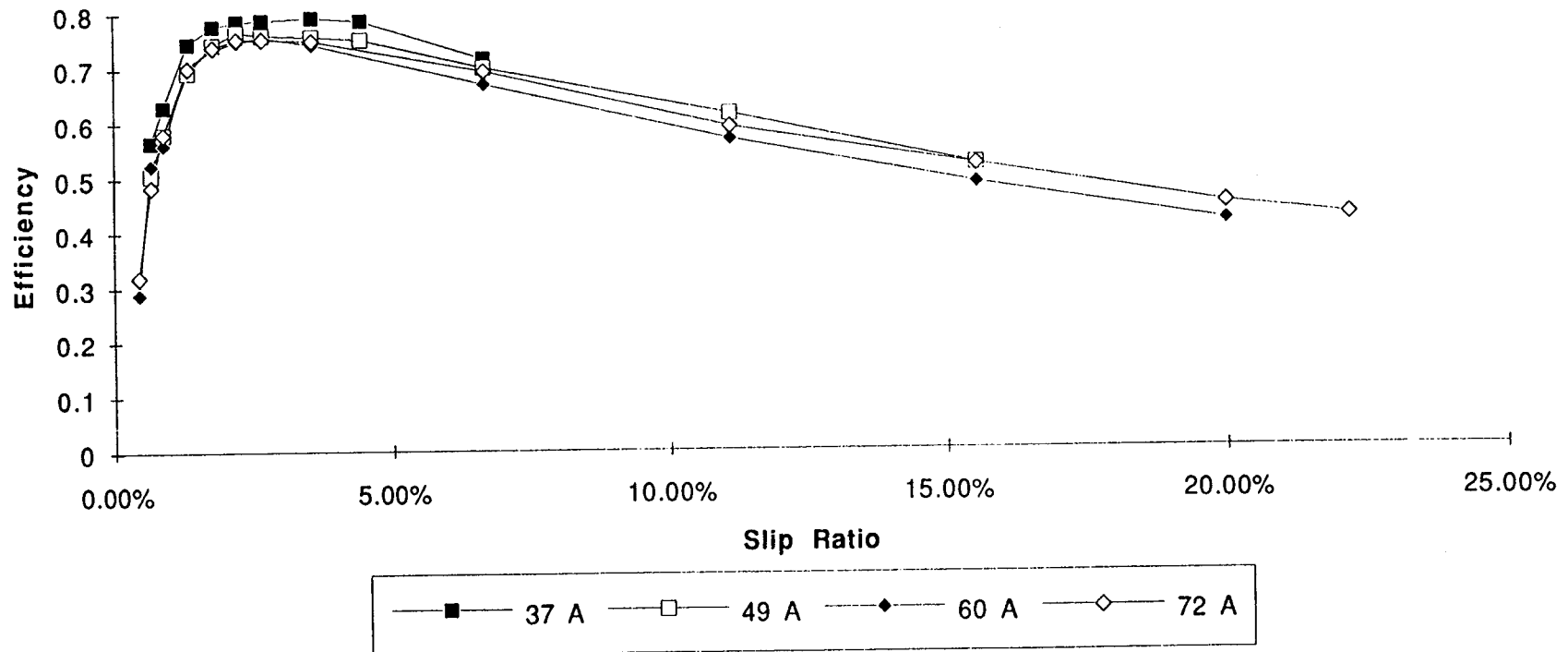
9K RPM, 70A, 5-28-93

Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		In-lbs			deg F	RPM
				Harmonics									
450	448	2240	0.44%	84.1	73	0.23	1410	1.81	12.75	0.320	0.13	181	8960
450	447	2235	0.67%	82.9	72.5	0.3	1820	3.55	25	0.485	0.13	189	8940
450	446	2230	0.89%	81.7	72.1	0.36	2090	4.88	34.5	0.581	0.13	193	8920
450	444	2220	1.33%	77.1	71.5	0.47	2560	7.22	51.25	0.701	0.13	196	8880
450	442	2210	1.78%	71.9	71.3	0.53	2710	8.07	57.5	0.740	0.13	195	8840
450	440	2200	2.22%	68.1	71.4	0.55	2650	8.03	57.5	0.753	0.13	193	8800
450	438	2190	2.67%	64.7	71.1	0.54	2510	7.61	54.75	0.754	0.13	191	8760
450	434	2170	3.56%	60.2	71.5	0.51	2190	6.61	48	0.751	0.13	188	8680
450	420	2100	6.67%	55.3	72.4	0.37	1480	4.13	31	0.694	0.2	184	8400
450	400	2000	11.11%	53.7	73	0.26	1040	2.48	19.5	0.592	0.34	180	8000
450	380	1900	15.56%	54.8	73	0.21	850	1.78	14.75	0.520	0.47	179	7600
450	360	1800	20.00%	55.6	73.2	0.18	730	1.31	11.5	0.448	0.61	179	7200
450	350	1750	22.22%	55.6	73.1	0.17	700	1.19	10.75	0.424	0.67	180	7000

Torque/Slip +50 Hz

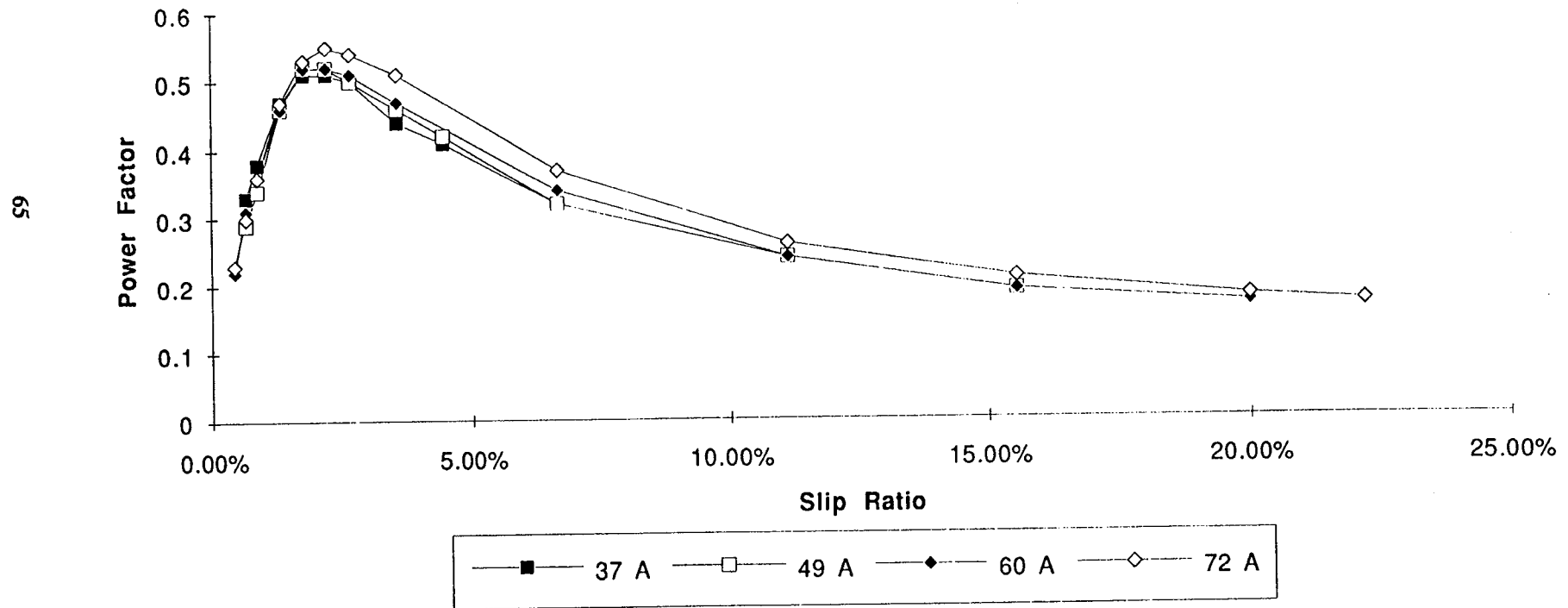
Motor Torque/Slip vs Current ($I_{ds}=I_{qs}$); Stator = 450 Hz (9000 RPM)

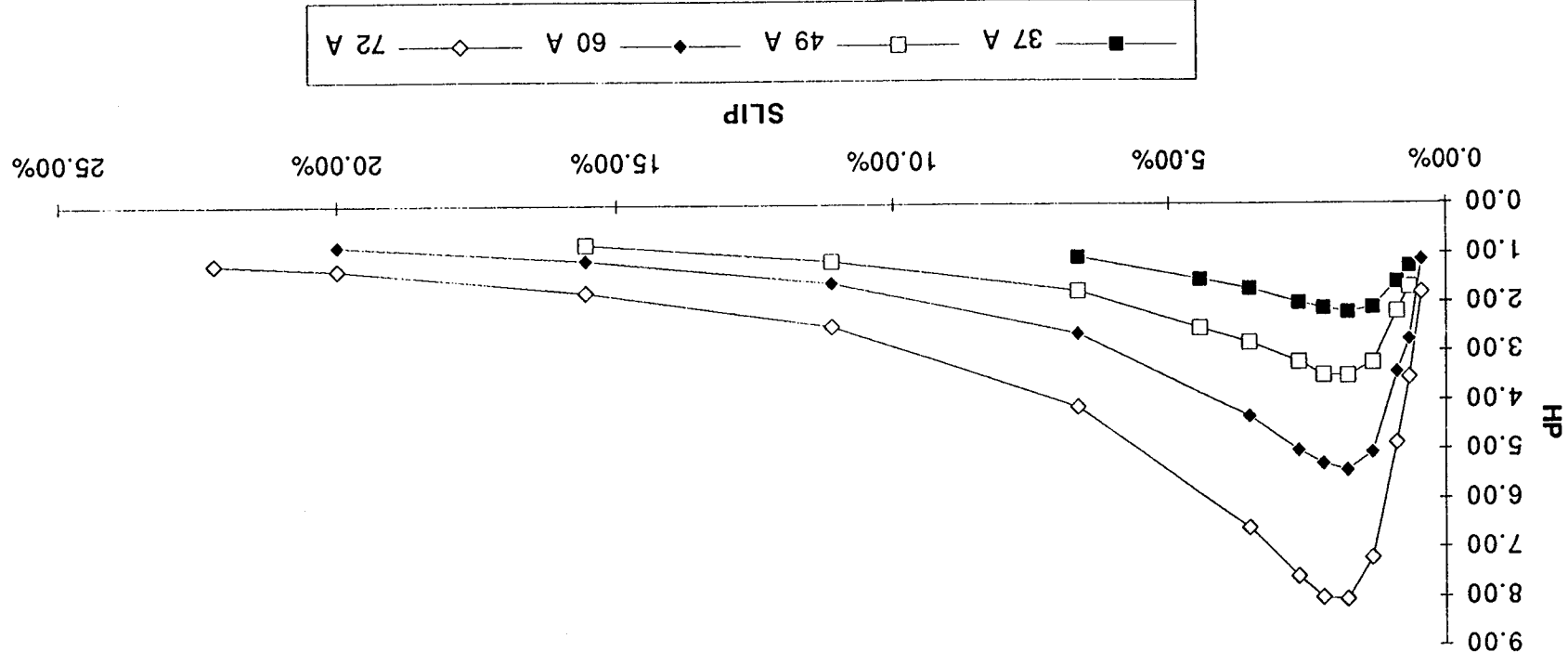


Efficiency/Slip vs Current ($I_{ds}=I_{qs}$); Stator = 450 Hz (9000 RPM)

PF/Slip 450 Hz

PF/Slip vs Current ($I_{ds}=I_{qs}$); Stator = 450 Hz (9000 RPM)



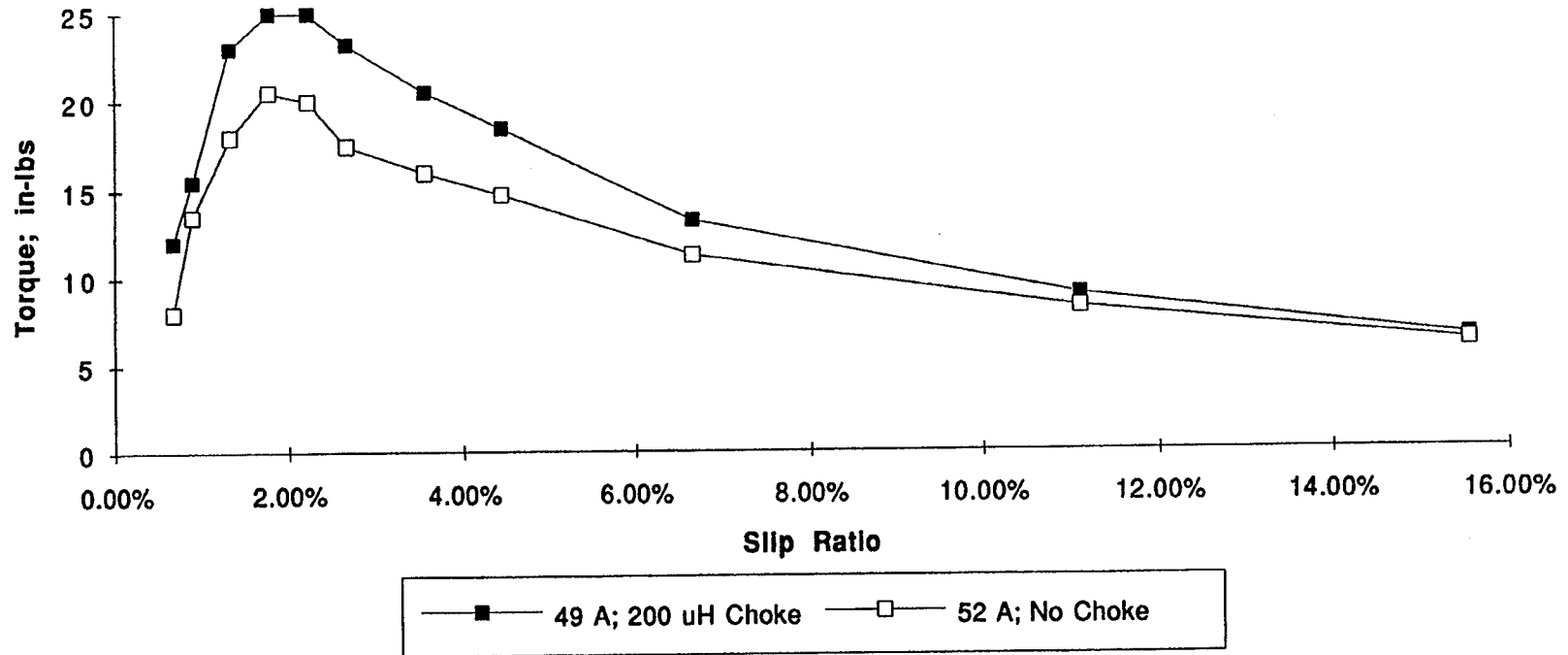


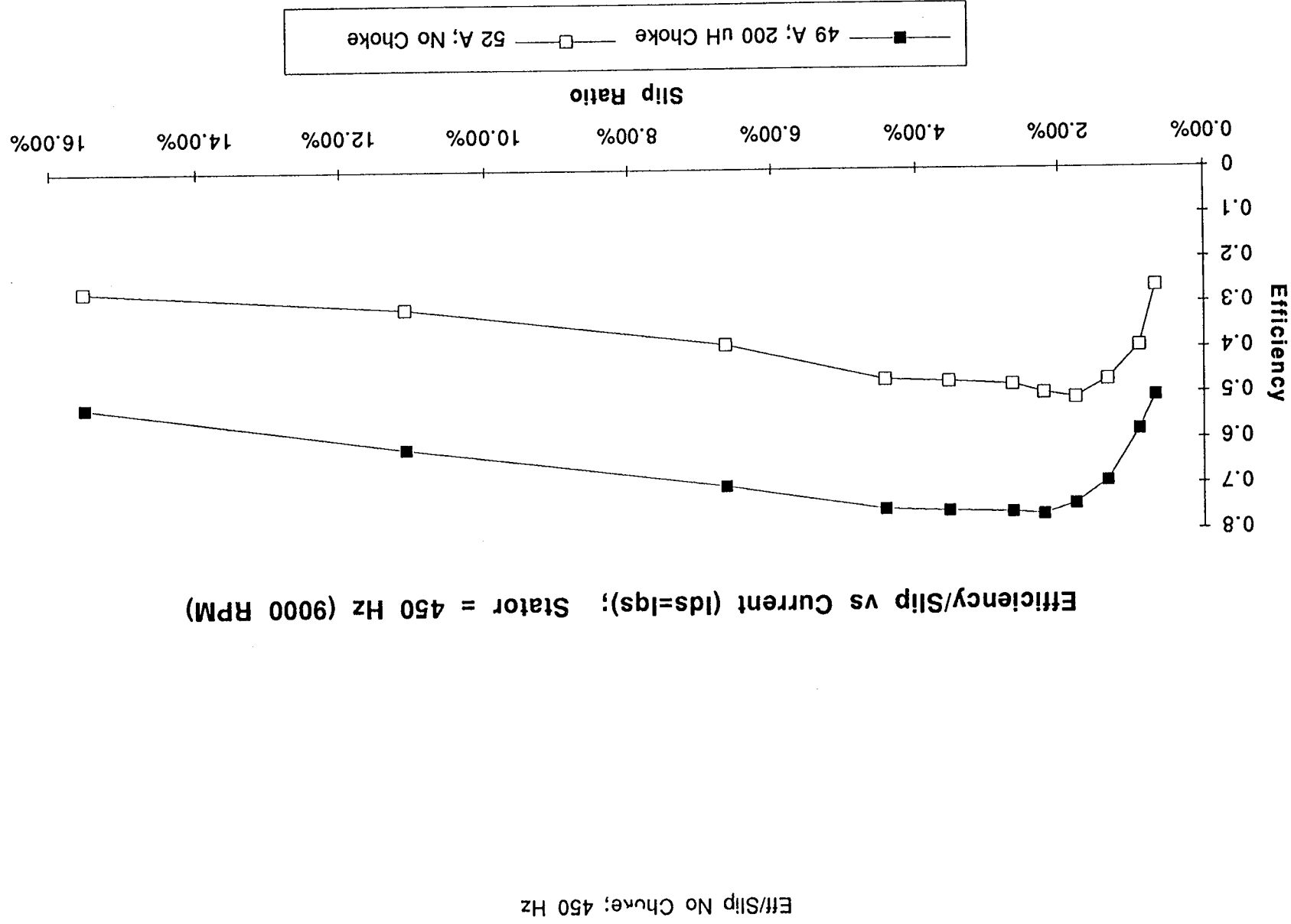
9K No Choke, 50A; 6-7-93

Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		in-lbs			deg F	RPM
				Harmonics									
450	447	2235	0.67%	117.3	54.7	0.17	1070	1.13	8.00	0.264	0.07	148	8940
450	446	2230	0.89%	113.7	53	0.19	1200	1.91	13.50	0.396	0.07	147	8920
450	444	2220	1.33%	112.4	52.9	0.23	1340	2.54	18.00	0.471	0.08	143	8880
450	442	2210	1.78%	110	53	0.24	1400	2.88	20.50	0.511	0.09	140	8840
450	440	2200	2.22%	109.8	53.6	0.23	1390	2.79	20.00	0.500	0.09	141	8800
450	438	2190	2.67%	109	52.2	0.22	1260	2.43	17.50	0.480	0.09	142	8760
450	434	2170	3.56%	111	52.2	0.2	1160	2.20	16.00	0.472	0.11	144	8680
450	430	2150	4.44%	108.2	51	0.19	1070	2.01	14.75	0.468	0.13	145	8600
450	420	2100	6.67%	111	52.7	0.17	960	1.50	11.25	0.388	0.2	147	8400
450	400	2000	11.11%	113	54.7	0.14	850	1.05	8.25	0.306	0.33	147	8000
450	380	1900	15.56%	107	52.5	0.13	710	0.75	6.25	0.264	0.47	148	7600

Torque/Slip No Choke; 450 Hz

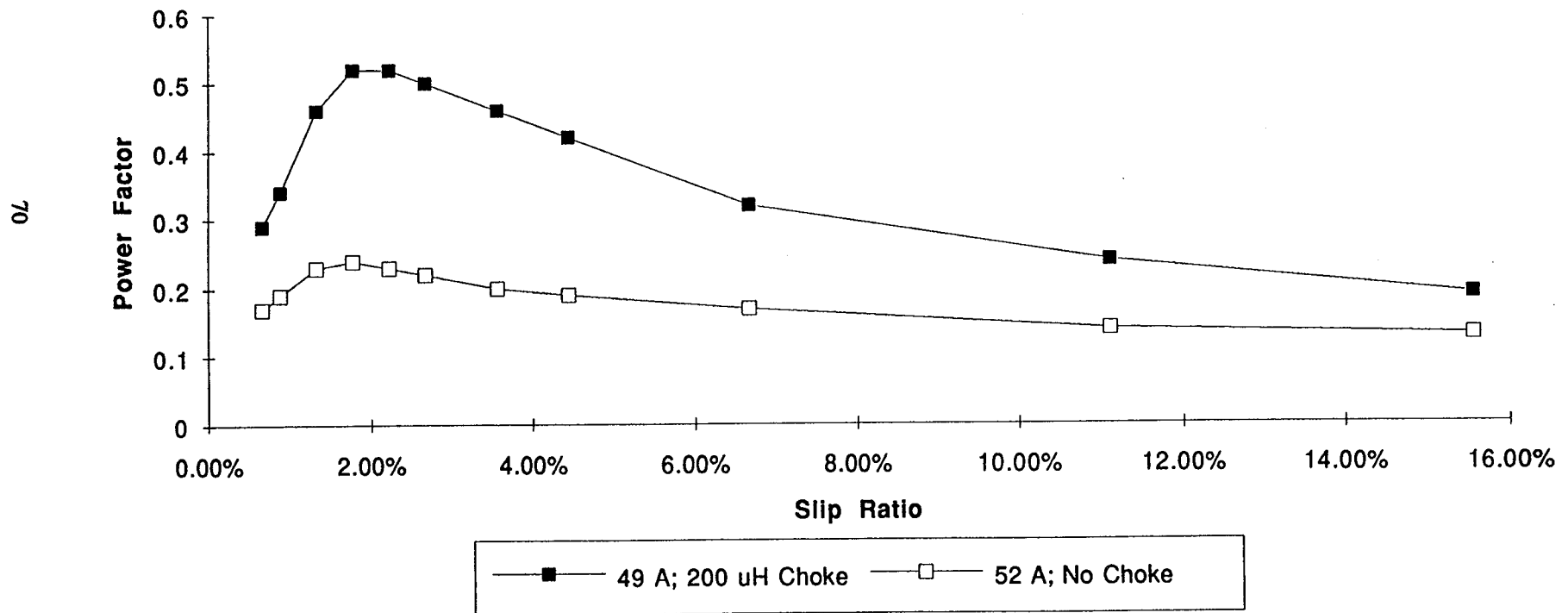
Torque/Slip vs Current ($I_{ds}=I_{qs}$); Stator = 450 Hz (9000 RPM)





PF/Slip; No Choke; 450 Hz

PF/Slip vs Current ($I_{ds}=I_{qs}$); Stator = 450 Hz (9000 RPM)



12K RPM, 40A; 6-1-93

Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		in-lbs			deg F	RPM
				Harmonics									
600	596	2980	0.67%	46.3	36	0.41	762	1.70	9	0.555	0.07	142	11920
600	594	2970	1.00%	48	35.6	0.5	861	2.45	13	0.708	0.07	145	11880
600	592	2960	1.33%	44	36.1	0.55	854	2.68	14.25	0.780	0.07	135	11840
600	590	2950	1.67%	39.6	36.4	0.56	811	2.57	13.75	0.789	0.07	130	11800
600	588	2940	2.00%	37.5	36.3	0.56	765	2.38	12.75	0.773	0.08	137	11760
600	586	2930	2.33%	36.4	36.8	0.55	735	2.28	12.25	0.771	0.09	137	11720
600	584	2920	2.67%	35.4	37	0.53	693	2.13	11.5	0.765	0.1	137	11680
600	580	2900	3.33%	32.6	37.2	0.48	576	1.79	9.75	0.775	0.13	137	11600

12K RPM, 50A; 6-1-93

Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		in-lbs			deg F	RPM
				Harmonics									
600	598	2990	0.33%	73.3	49	0.25	887	1.38	7.25	0.386	0.09	154	11960
600	596	2980	0.67%	68.5	48.2	0.4	1308	3.22	17	0.611	0.09	151	11920
600	594	2970	1.00%	62.8	47.7	0.5	1501	4.29	22.75	0.710	0.09	148	11880
600	592	2960	1.33%	57.6	47.5	0.55	1520	4.60	24.5	0.753	0.09	145	11840
600	590	2950	1.67%	52.2	47.4	0.59	1448	4.63	24.75	0.796	0.09	144	11800
600	588	2940	2.00%	49	47.8	0.58	1352	4.38	23.5	0.807	0.09	143	11760
600	586	2930	2.33%	47.5	47.9	0.57	1306	4.14	22.25	0.788	0.09	143	11720
600	584	2920	2.67%	45	48.4	0.54	1178	3.80	20.5	0.802	0.11	145	11680
600	580	2900	3.33%	42.8	48.7	0.51	1055	3.36	18.25	0.792	0.13	145	11600
600	560	2800	6.67%	39.6	50	0.32	636	1.82	10.25	0.712	0.27	139	11200
600	550	2750	8.33%	39.6	49.5	0.28	544	1.31	7.5	0.598	0.34	169	11000

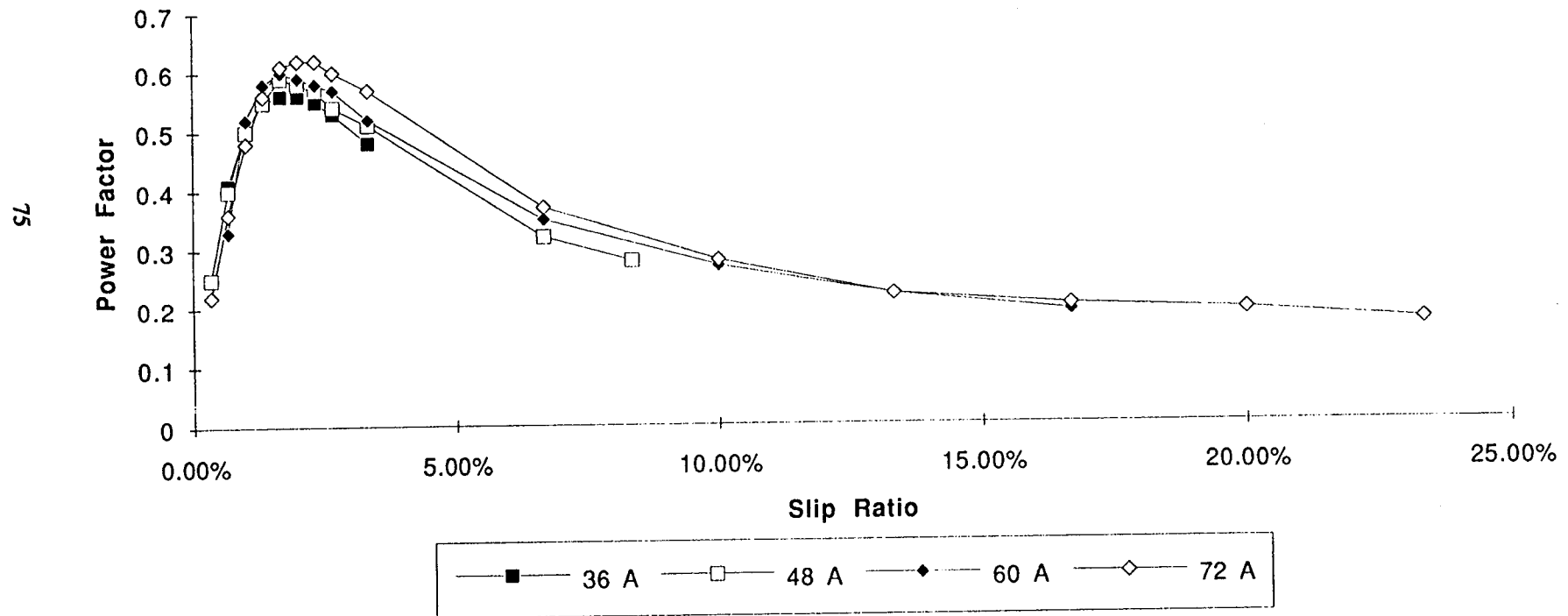
[illegible]

12K RPM, 70A; 6-1-93

Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		in-lbs			deg F	RPM
				Harmonics									
600	598	2990	0.33%	102	71.5	0.22	1590	2.37	12.5	0.371	0.13	218	11960
600	596	2980	0.67%	98.7	70	0.36	2540	6.10	32.25	0.597	0.13	208	11920
600	594	2970	1.00%	93.3	70	0.48	3120	8.62	45.75	0.687	0.13	201	11880
600	592	2960	1.33%	86.5	70	0.56	3390	10.00	53.25	0.734	0.13	195	11840
600	590	2950	1.67%	79.9	70.4	0.61	3450	10.77	57.5	0.776	0.13	189	11800
600	588	2940	2.00%	75.1	71.4	0.62	3330	10.50	56.25	0.784	0.13	185	11760
600	586	2930	2.33%	71.4	71.2	0.62	3170	10.09	54.25	0.791	0.13	181	11720
600	584	2920	2.67%	68.2	72.4	0.6	2980	9.59	51.75	0.800	0.13	175	11680
600	580	2900	3.33%	63.3	72.6	0.57	2620	8.42	45.75	0.799	0.13	165	11600
600	560	2800	6.67%	55.1	73.1	0.37	1490	4.27	24	0.712	0.27	158	11200
600	540	2700	10.00%	53.9	74.2	0.28	1130	2.91	17	0.641	0.4	153	10800
600	520	2600	13.33%	53.8	74.6	0.22	873	1.98	12	0.564	0.53	130	10400
600	500	2500	16.67%	54.2	74.8	0.2	800	1.63	10.25	0.506	0.67	145	10000
600	480	2400	20.00%	54.8	74.4	0.19	750	1.33	8.75	0.442	0.81	170	9600
600	460	2300	23.33%	54.7	74.5	0.17	710	1.13	7.75	0.396	0.93	177	9200

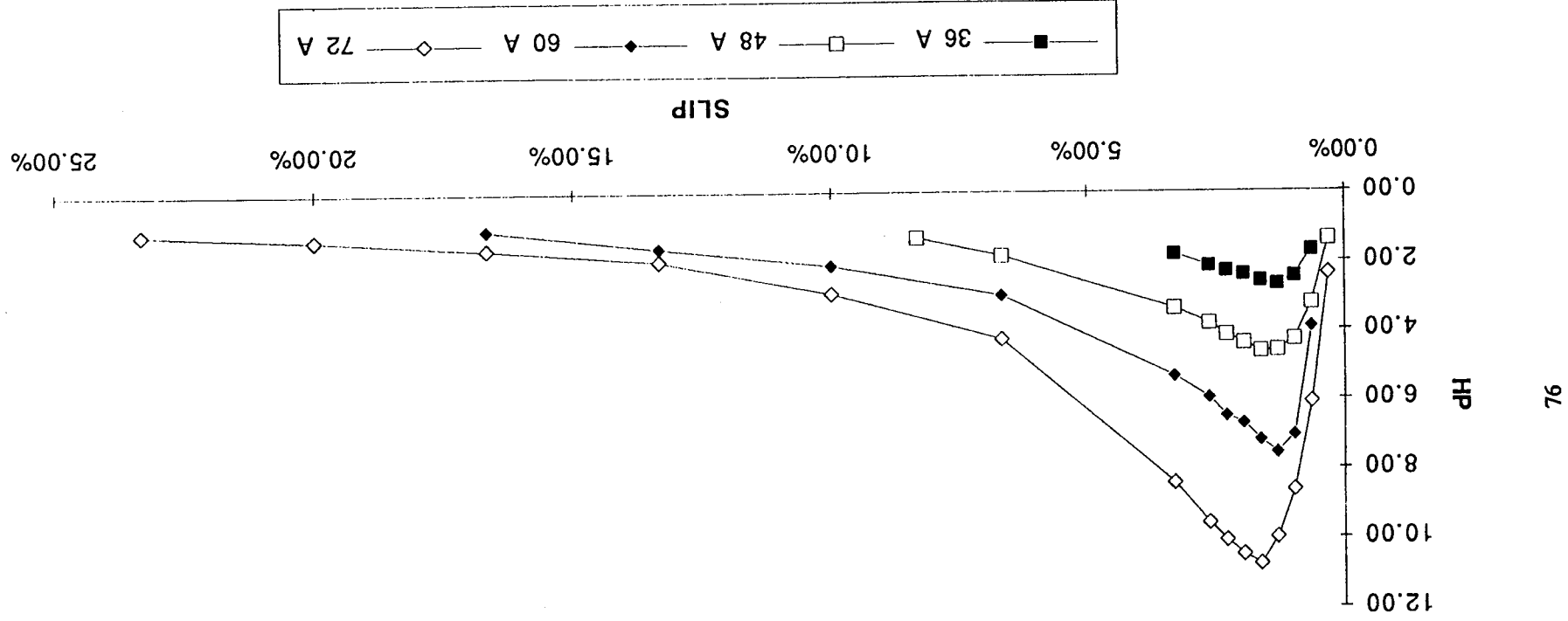
PF/Slip 600 Hz

PF/Slip vs Current ($I_{ds}=I_{qs}$); Stator = 600 Hz (12000 RPM)



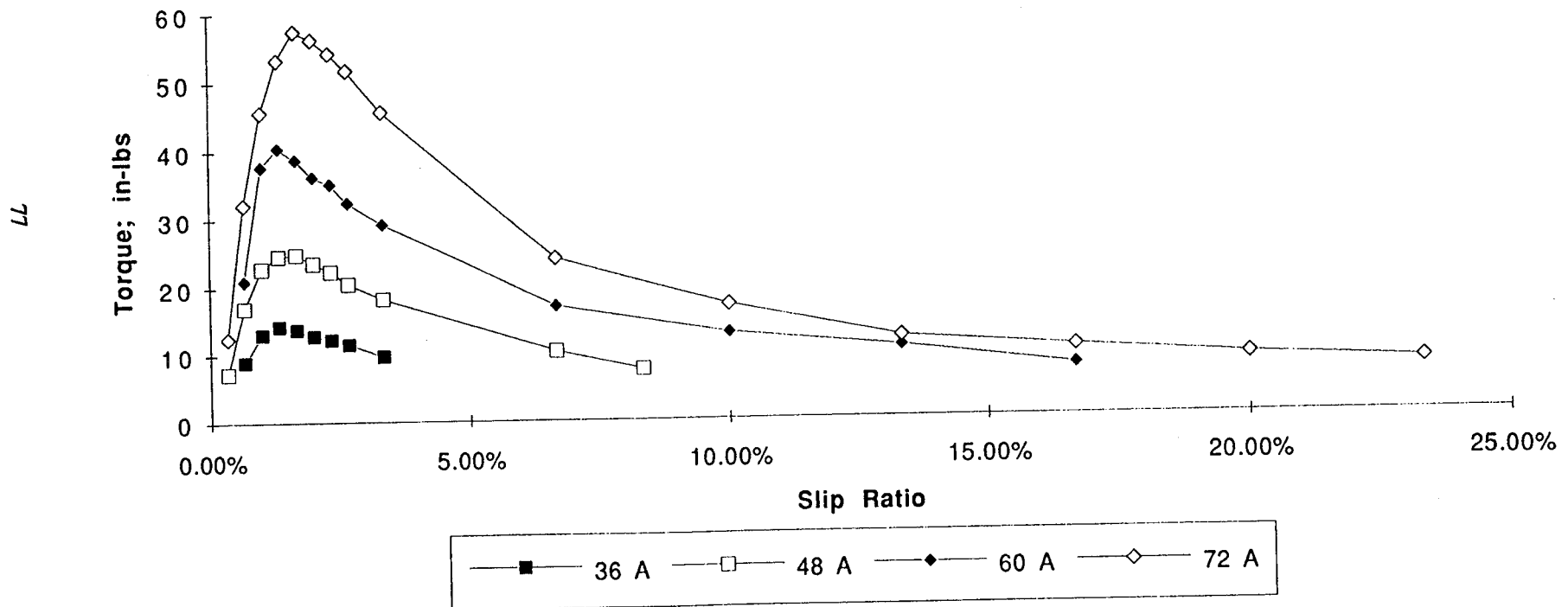
HP/SLIP ~ 0 Hz

HP/SLIP vs Current (I_{ds}=I_{qs}): Stator = 600 Hz (12000 RPM)



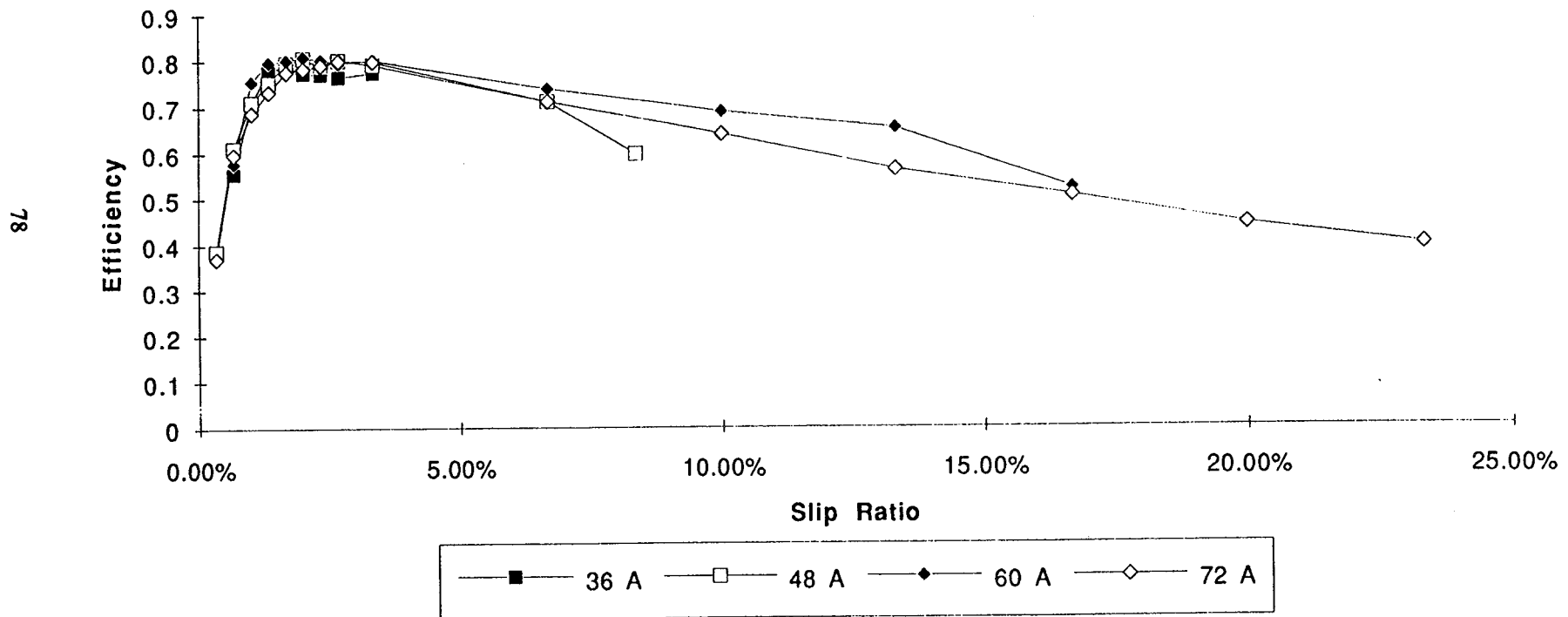
Torque/Slip 500 Hz

Torque/Slip vs Current ($I_{ds}=I_{qs}$); Stator = 600 Hz (12000 RPM)



Eff/Slip vs Hz

Efficiency/Slip vs Current ($I_{ds}=I_{qs}$); Stator = 600 Hz (12000 RPM)



14K RPM, 40A; 6-4-93

Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		in-lbs			deg F	RPM
				Harmonics									
700	696	3480	0.57%	54.7	36	0.45	890	2.26	10.25	0.633	0.07	121	13920
700	694	3470	0.86%	51	36	0.53	970	2.59	11.75	0.663	0.07	121	13880
700	692	3460	1.14%	47	35.8	0.57	935	2.69	12.25	0.715	0.07	121	13840
700	690	3450	1.43%	42	35.9	0.59	895	2.57	11.75	0.715	0.07	118	13800
700	688	3440	1.71%	40	36.3	0.59	845	2.40	11	0.707	0.08	117	13760
700	686	3430	2.00%	38	36.5	0.57	798	2.29	10.5	0.712	0.09	116	13720
700	684	3420	2.29%	36.5	36.6	0.55	749	2.17	10	0.721	0.1	115	13680
700	682	3410	2.57%	34.8	36.8	0.52	666	1.95	9	0.727	0.12	114	13640
700	680	3400	2.86%	34.1	37.1	0.51	640	1.78	8.25	0.692	0.13	113	13600
700	678	3390	3.14%	33.8	37.2	0.49	611	1.72	8	0.701	0.14	113	13560
700	676	3380	3.43%	33.3	37.4	0.45	560	1.56	7.25	0.691	0.16	112	13520

14K RPM, 50A; 6-4-93

Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		in-lbs			deg F	RPM
				Harmonics									
700	698	3490	0.29%	82	48.8	0.27	1106	1.94	8.75	0.436	0.08	160	13960
700	696	3480	0.57%	76.7	48	0.41	1510	4.09	18.5	0.673	0.08	158	13920
700	694	3470	0.86%	71.2	47.4	0.51	1697	4.85	22	0.710	0.08	149	13880
700	692	3460	1.14%	64.2	47.3	0.57	1730	5.22	23.75	0.750	0.08	145	13840
700	690	3450	1.43%	57	47	0.61	1660	5.26	24	0.787	0.08	139	13800
700	688	3440	1.71%	52.3	47.4	0.6	1504	4.86	22.25	0.803	0.09	136	13760
700	686	3430	2.00%	48.7	47.9	0.59	1384	4.35	20	0.782	0.1	134	13720
700	684	3420	2.29%	47.4	47.8	0.57	1299	4.07	18.75	0.779	0.11	135	13680
700	682	3410	2.57%	46	48.1	0.55	1222	3.90	18	0.793	0.12	131	13640
700	680	3400	2.86%	45.3	48.4	0.53	1158	3.61	16.75	0.776	0.13	129	13600
700	678	3390	3.14%	44.3	48.5	0.51	1092	3.33	15.5	0.759	0.14	127	13560
700	676	3380	3.43%	42.5	48.7	0.47	963	2.84	13.25	0.734	0.16	117	13520
700	674	3370	3.71%	42.9	48.8	0.45	938	2.73	12.75	0.723	0.17	122	13480
700	660	3300	5.71%	41.2	49.4	0.34	687	1.83	8.75	0.663	0.27	125	13200
700	640	3200	8.57%	41.6	50.6	0.27	556	1.27	6.25	0.568	0.27	125	12800

14K RPM, 60A; 6-4-93

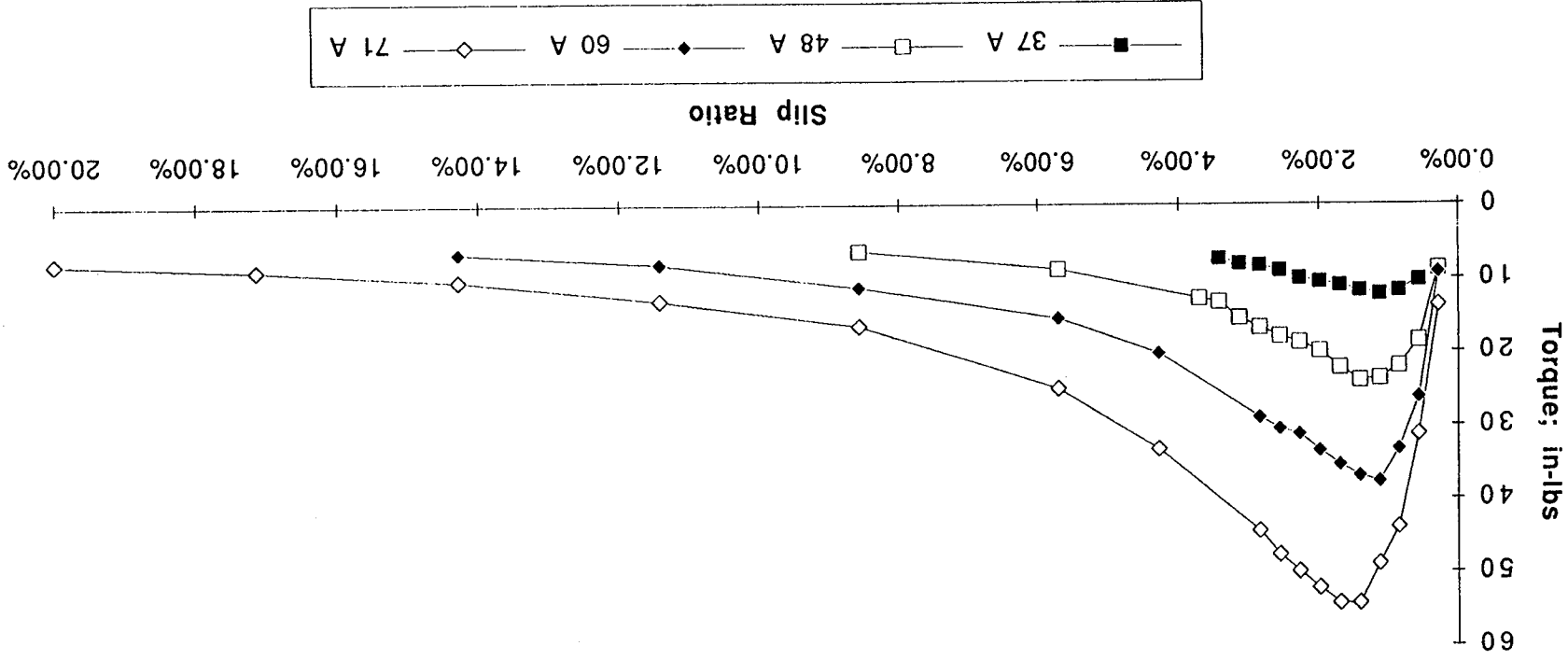
Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		in-lbs			deg F	RPM
				Harmonics									
700	698	3490	0.29%	96.6	60	0.23	1340	2.05	9.25	0.380	0.08	154	13960
700	696	3480	0.57%	91.5	58.9	0.41	2195	5.80	26.25	0.657	0.08	173	13920
700	694	3470	0.86%	85.3	58.5	0.51	2560	7.32	33.25	0.711	0.1	179	13880
700	692	3460	1.14%	77.1	59.1	0.59	2677	8.29	37.75	0.770	0.1	177	13840
700	690	3450	1.43%	69.9	59.4	0.63	2612	8.10	37	0.771	0.11	175	13800
700	688	3440	1.71%	65.7	59.9	0.63	2460	7.75	35.5	0.783	0.11	172	13760
700	686	3430	2.00%	63	60.2	0.62	2340	7.29	33.5	0.775	0.11	170	13720
700	684	3420	2.29%	60.1	60	0.6	2175	6.78	31.25	0.776	0.11	168	13680
700	682	3410	2.57%	58.6	60.4	0.59	2070	6.60	30.5	0.793	0.12	165	13640
700	680	3400	2.86%	57	60.3	0.57	1962	6.26	29	0.793	0.13	163	13600
700	670	3350	4.29%	51.8	60.9	0.46	1438	4.31	20.25	0.745	0.2	161	13400
700	660	3300	5.71%	50	61.4	0.38	1166	3.25	15.5	0.692	0.27	159	13200
700	640	3200	8.57%	49	61.9	0.29	883	2.28	11.25	0.643	0.4	157	12800
700	620	3100	11.43%	48.5	61.9	0.23	704	1.57	8	0.556	0.53	150	12400
700	600	3000	14.29%	48	62.2	0.2	626	1.24	6.5	0.492	0.67	154	12000

14K RPM, 70A; 6-4-93

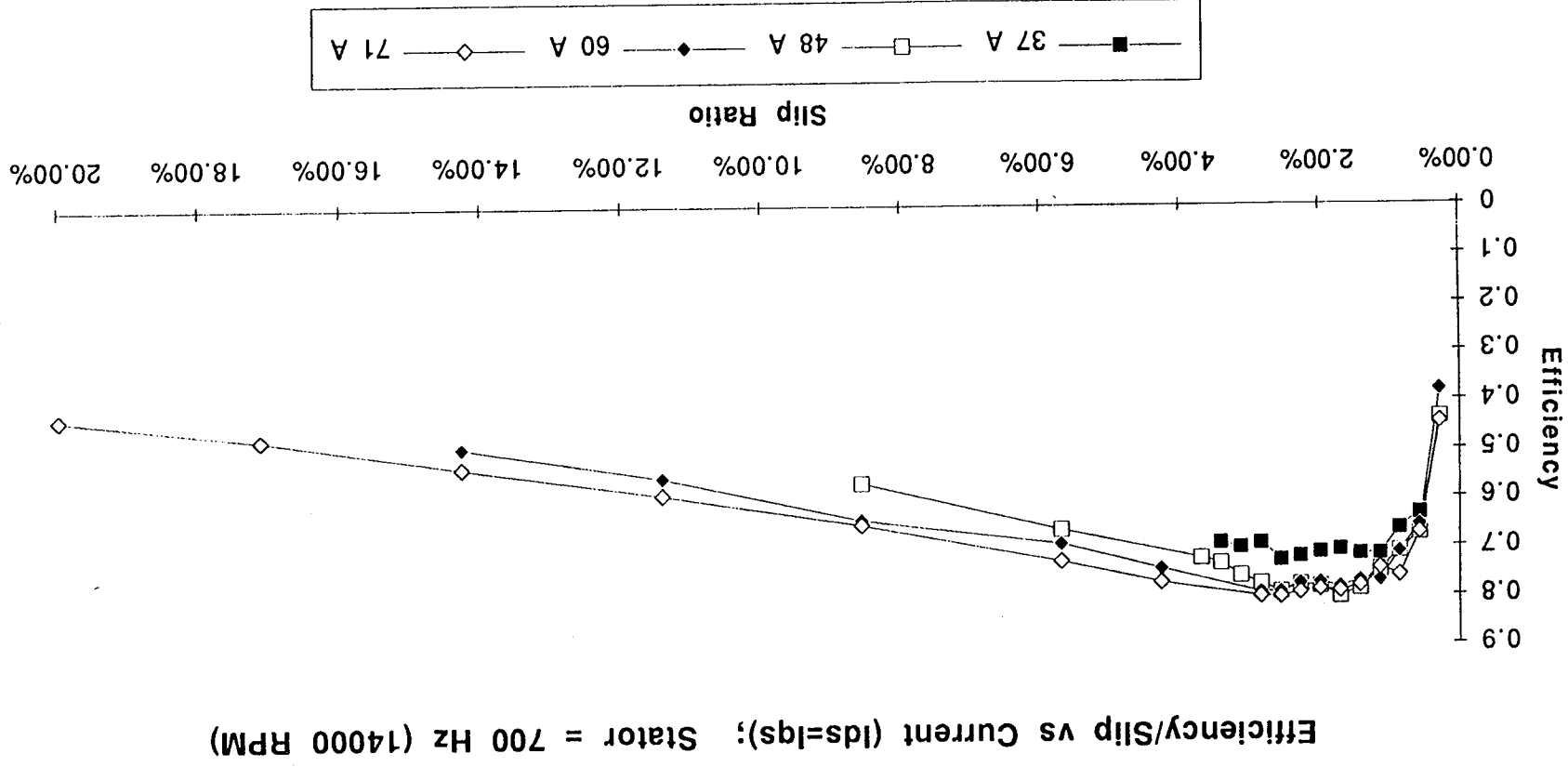
Stator	fs-fr	Dyno		Motor	Motor		Motor	Dyno	Motor	Motor		Motor	Motor
FREQ	FREQ	Speed	Slip	Volts	Current	PF	Power (W)	HP	Torque	Eff.	Ks	Temp	Speed
Hz	Hz	RPM	%	L-N	(A/phase)		1 Phase		in-lbs			deg F	RPM
				Harmonics									
700	698	3490	0.29%	106.5	62.2	0.26	1700	3.05	13.75	0.446	0.13	226	13960
700	696	3480	0.57%	105	63.8	0.38	2550	6.90	31.25	0.673	0.13	222	13920
700	694	3470	0.86%	100.5	65.5	0.49	3170	9.69	44	0.760	0.13	216	13880
700	692	3460	1.14%	94.7	67.2	0.56	3590	10.76	49	0.745	0.13	212	13840
700	690	3450	1.43%	87.6	68.9	0.63	3780	11.88	54.25	0.781	0.13	209	13800
700	688	3440	1.71%	82.4	69.9	0.64	3720	11.84	54.25	0.792	0.13	205	13760
700	686	3430	2.00%	78.4	70.8	0.65	3590	11.37	52.25	0.788	0.13	202	13720
700	684	3420	2.29%	74.5	71.4	0.64	3400	10.85	50	0.794	0.13	197	13680
700	682	3410	2.57%	71	71.9	0.63	3200	10.33	47.75	0.803	0.13	192	13640
700	680	3400	2.86%	67.7	72.3	0.61	2980	9.60	44.5	0.801	0.14	186	13600
700	670	3350	4.29%	60.6	73.4	0.51	2275	7.07	33.25	0.773	0.2	175	13400
700	660	3300	5.71%	57.6	73.6	0.42	1786	5.24	25	0.729	0.27	170	13200
700	640	3200	8.57%	56	73.7	0.31	1276	3.35	16.5	0.653	0.4	160	12800
700	620	3100	11.43%	55.3	74.3	0.26	1076	2.56	13	0.591	0.53	167	12400
700	600	3000	14.29%	55.9	74.6	0.22	909	1.95	10.25	0.534	0.67	161	12000
700	580	2900	17.14%	56.2	74.8	0.2	845	1.61	8.75	0.474	0.81	170	11600
700	560	2800	20.00%	56.1	74.9	0.19	800	1.38	7.75	0.428	0.93	178	11200

2

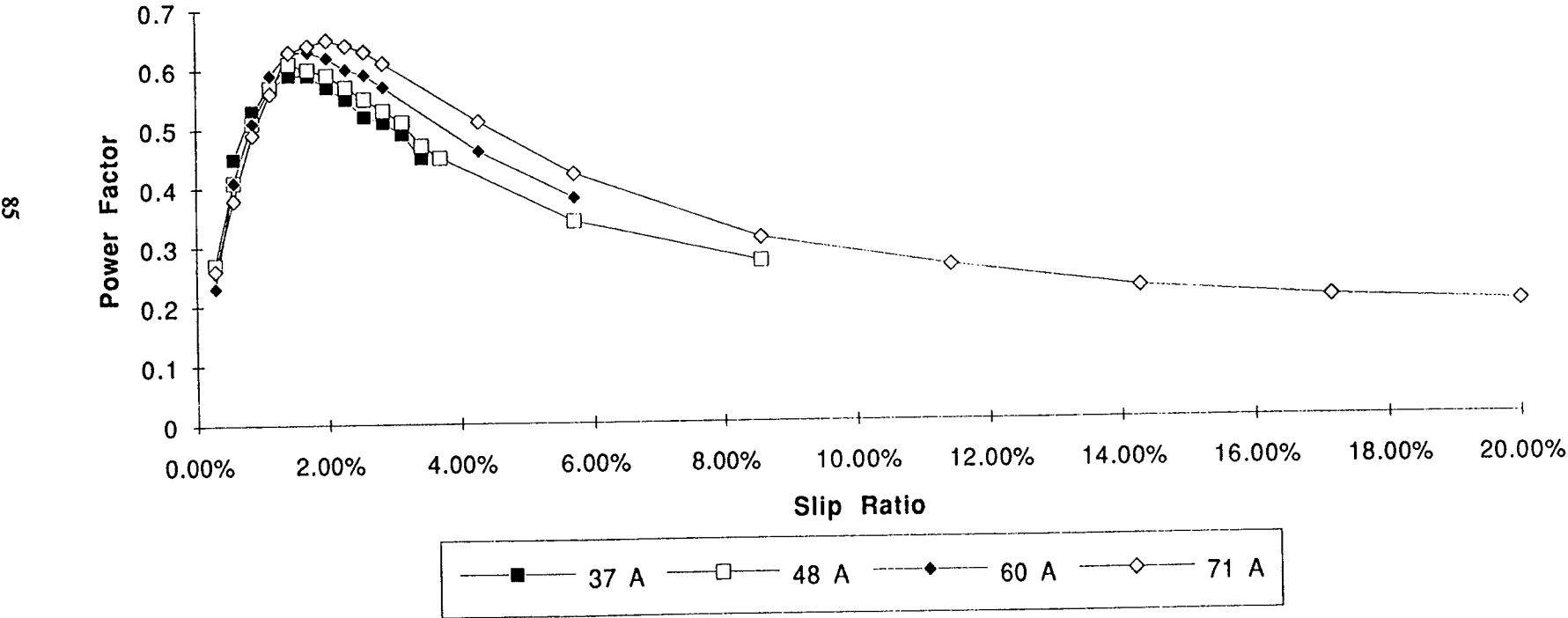
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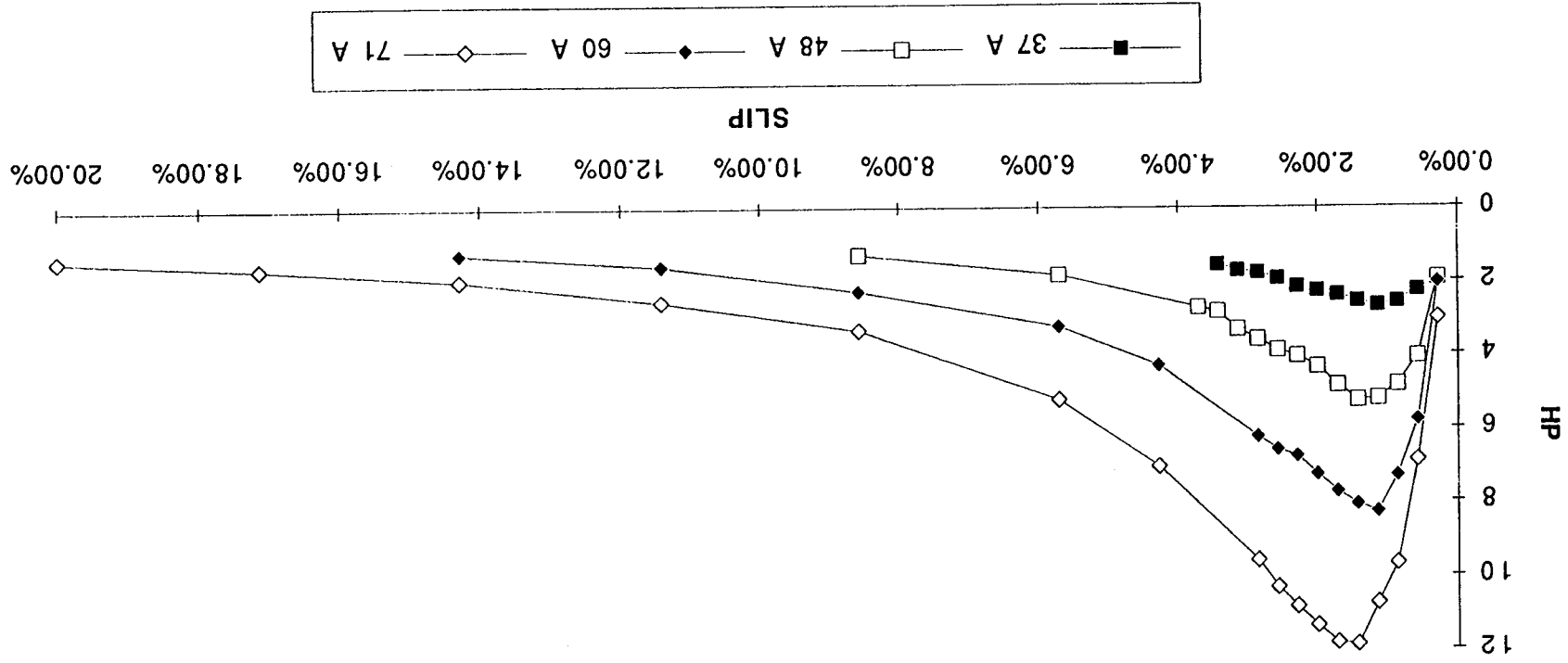


Torque/Slip, 00 Hz



PF/Slip vs Current (I_{ds}=I_{qs}); Stator = 700 Hz (14000 RPM)





HP/SLIP vs Current ($I_{ds}=I_{qs}$); Stator = 700 Hz (14000 RPM)

APPENDIX F

System Efficiency Data

The tables containing the measured data have column headings defined below:

<u>Heading</u>	<u>Definition</u>
AC Current Amps	The AC current moving between the inverter output and the motor controller input.
AC PF	The power factor in the line between the inverter output and motor controller.
AC Power (W) 20 KHz	The power out of the inverter and into the motor controller.
DC Current	The inverter DC input current.
DC Volts	The DC voltage on the input to the 20 KHz inverter.
Dyno HP	The horsepower out of the motor, adjusted for gearbox inefficiencies.
Dyno Speed RPM	The speed of the dynamometer shaft.
Inverter % eff.	The efficiency of the 20 KHz inverter.
Ks	The slip constant used in computing the commanded motor slip.
Motor Temp deg F	The temperature of the stator in degrees Fahrenheit.
Motor Torque in-lbs	The motor torque output at the motor shaft.
Power Stg % eff.	The efficiency of the motor controllers power stage.
Stator FREQ, Hz	The stator current drive frequency.
System % eff.	The efficiency of the inverter , controller and motor.

System Efficiency Test Notes

July 1993

- In order to calculate Inverter, Power Stage (controller), Motor, and System Efficiency, power must be measured at four test points.
 - 1) DC power input to the inverter.
 - 2) AC power output from the inverter and into the power stage.
 - 3) Power into the motor.
 - 4) Power out of the motor.
- Due to availability of only one power analyzer (Yokogawa 2355), the data used in these calculations was gathered in a series of two measurements.
- The first set of measurements was performed when the "Motor Curves" data was gathered. The second set of data duplicated the test conditions of the "Motor Curves" data at select operating points and recorded the Inverter Output Power, Current and Power Factor.
- A source of error is introduced when re-creating test conditions present in the first set of measurements. This error is caused by the tendency of the rotor resistance to vary over temperature. If the rotor resistance changes, the corresponding slip value to produce a given torque changes also. This results in a torque error.
- The measurements made in the attached document minimized this torque error by monitoring the temperature of the stator, and where possible making the measurements at the same temperature as the "Motor Curves" data. If the temperature in the secondary measurements was difficult to maintain, the slip was adjusted to produce the same torque as in the previous set of measurements. This adjustment was typically small.
- The difficulty in making these measurements limited the number of data points that could be recorded within a reasonable time frame. For this reason the data was gathered at peak efficiency and several adjacent operating points.

System Efficiency: 150 Hz

Stator FREQ	Dyno Speed	Motor Torque	Dyno HP	DC Volts	DC Current	AC PF	AC Power (W)	AC Current	Inverter % eff.	Power Stg % eff.	System % eff.	Ks	Motor Temp deg F
Hz	RPM	In-lbs					20 KHz	Amps					
40 A/Phase													
150	730	12.5	0.58	150	24.2	0.14	1730	35.5	48	53	12	0.07	111
150	710	14.75	0.66	150	24.7	0.14	1780	35.1	48	49	13	0.07	118
150	680	11.5	0.50	150	23.8	0.14	1670	35.3	47	42	10	0.1	120
150	600	7	0.27	150	22.6	0.12	1500	35	44	32	6	0.2	121
50 A/Phase													
150	730	17.5	0.81	150	28.9	0.14	2400	48.1	55	61	14	0.09	150
150	700	27	1.20	150	31.1	0.16	2720	49.3	58	57	19	0.09	147
150	680	22.5	0.97	150	29.9	0.15	2560	47.8	57	51	16	0.1	141
150	600	13.25	0.50	150	27.1	0.14	2160	43.5	53	41	9	0.2	130
60 A/Phase													
150	730	21.5	1.00	152.7	33.3	0.15	3060	52.6	60	66	15	0.07	121
150	700	38	1.69	152.7	37.2	0.17	3650	52.6	64	60	22	0.1	120
150	680	33.75	1.46	152.7	36.4	0.16	3520	52.5	63	55	20	0.1	127
150	600	20.25	0.77	152.7	33.1	0.15	3050	49	60	44	11	0.2	133
70 A/Phase													
150	730	39	1.81	153.2	42	0.19	4380	57.8	68	70	21	0.13	170
150	710	56.5	2.55	153.2	45.7	0.21	4960	58.4	71	67	27	0.13	166
150	680	50.25	2.17	153.2	44	0.2	4720	60	70	60	24	0.13	160
150	600	28.25	1.08	153.2	39.4	0.16	3980	59.8	66	46	13	0.2	144

System Efficiency; 300 Hz

Stator	Dyno	Motor	Dyno	DC	DC	AC	AC	AC	Inverter	Powr Stg	System		Motor
FREQ	Speed	Torque	HP	Volts	Current	PF	Power (W)	Current	% eff.	% eff.	% eff.	Ks	Temp
Hz	RPM	In-lbs					20 KHz	Amps					deg F
40 A/Phase													
301	1480	12.5	1.17	151	28.3	0.18	2340	37.3	55	67	20	0.1	134
300	1470	13.25	1.24	151	28.3	0.18	2400	38	56	65	22	0.08	136
300	1450	12.25	1.13	151	28.3	0.17	2330	38.9	55	58	20	0.07	132
300	1420	11	0.99	151	27.5	0.16	2210	38.7	53	55	18	0.09	130
50 A/Phase													
299.2	1480	14.25	1.34	151	32.1	0.18	2860	41.5	59	79	21	0.065	126
299.2	1470	20.5	1.91	151	35.8	0.21	3310	41.8	61	78	26	0.065	124
300	1450	23	2.12	151	35.8	0.21	3480	43	64	72	29	0.09	140
300	1420	17.75	1.60	151	33.7	0.18	3120	43.8	61	64	23	0.11	134
70 A/Phase													
300	1480	35.5	3.33	155	48.3	0.25	5440	52.6	73	89	33	0.11	120
300	1470	49.5	4.62	155	54.4	0.29	6430	52.5	76	87	41	0.11	125
300	1450	54.75	5.04	155	56.6	0.3	6800	49	78	82	43	0.2	132
300	1420	46.75	4.21	155	52.9	0.27	6180	57.8	75	75	38	0.13	150

System Efficiency; 450 Hz

Stator FREQ Hz	Dyno Speed RPM	Motor Torque in-lbs	Dyno HP	DC Volts	DC Current	AC PF	AC Power (W) 20 KHz	AC Current Amps	Inverter % eff.	Powr Stg % eff.	System % eff.	Ks	Motor Temp deg F
50 A/Phase													
450	2230	15.5	2.19	151	34.4	0.23	3300	41.2	64	85	32	0.07	141
450	2210	26.75	3.75	151	41.6	0.29	4390	44	70	80	45	0.09	140
450	2200	25.25	3.53	151	40.8	0.27	4250	45.1	69	80	43	0.1	141
450	2170	21.25	2.93	151	37.8	0.24	3800	45.9	67	73	38	0.11	132
70 A/Phase													
450	2230	34	4.81	153	56.6	0.34	6600	54.7	76	95	41	0.13	200
450	2210	57.25	8.03	153	72.7	0.44	9170	60.2	82	91	54	0.13	193
450	2200	57.5	8.03	153	72.7	0.43	9190	61.2	83	90	54	0.13	182
450	2170	48	6.61	153	66	0.37	8160	62.6	81	84	49	0.13	177

System Efficiency; 600 Hz

Stator	Dyno	Motor	Dyno	DC	DC	AC	AC	AC	Inverter	Powr Stg	System		Motor
FREQ	Speed	Torque	HP	Volts	Current	PF	Power (W)	Current	% eff.	% eff.	% eff.	Ks	Temp
Hz	RPM	in-lbs					20 KHz	Amps					deg F
50 A/Phase													
600	2970	22.5	4.24	152	44.5	0.34	5000	40.8	74	90	47	0.09	155
600	2950	24.25	4.54	152	46	0.33	5090	42.6	73	88	48	0.09	147
600	2930	22.25	4.14	152	44.3	0.31	4780	43.3	71	82	46	0.09	149
600	2900	18.25	3.36	152	40.4	0.26	4210	45.3	69	75	41	0.13	148
70 A/Phase													
600	2970	45.5	8.58	155	74.8	0.45	9660	60	83	97	55	0.13	191
600	2950	57	10.67	155	82.8	0.48	10930	63.9	85	95	62	0.13	192
600	2930	53.25	9.90	155	79.8	0.47	10390	62.9	84	92	60	0.13	192
600	2800	24.25	4.31	155	53.5	0.28	6300	62.5	76	71	39	0.27	185

System Efficiency; 700 Hz

Stator	Dyno	Motor	Dyno	DC	DC	AC	AC	AC	Inverter	Powr Stg	System		Motor
FREQ	Speed	Torque	HP	Volts	Current	PF	Power (W)	Current	% eff.	% eff.	% eff.	Ks	Temp
Hz	RPM	in-lbs					20 KHz	Amps					deg F
50 A/Phase													
700	3480	17.75	3.92	154	44.45	0.32	4780	40.8	70	95	43	0.08	157
700	3450	23.25	5.09	154	50.1	0.38	5730	42.5	74	87	49	0.08	141
700	3440	21	4.58	151	48.4	0.36	5370	42.3	73	84	47	0.09	136
700	3410	16.5	3.57	151	43.4	0.3	4610	43.4	70	80	41	0.12	130
70 A/Phase													
700	3480	31	6.85	178	62.6	0.44	8370	52	75	91	46	0.13	220
700	3450	53.75	11.77	178	82.9	0.54	11930	62.2	81	95	59	0.13	209
699.3	3440	53.5	11.68	178	82.9	0.54	11900	62.1	81	94	59	0.12	205
699.2	3410	47.25	10.23	177	76.8	0.51	10790	59.9	79	89	56	0.12	191

APPENDIX G

Loss/Efficiency Data

The tables containing the measured data have column headings defined below:

<u>Heading</u>	<u>Definition</u>
Commanded Speed, RPM	The commanded motor speed.
DC Current	The input current (amps) to the inverter.
DC Volts	The DC voltage measured at the input to the inverter.
Dyno Speed RPM	The speed of the dynamometer shaft.
Dyno Torque in-lbs	The torque output of the gearbox prior to compensation for gearbox friction.
fs-fr FREQ, Hz	The difference between the stator and rotor frequencies.
Gear Temp deg F	The temperature of the gearbox in degrees Fahrenheit.
Ids*	The commanded value of the direct axis current.
Inv/Cont Eff. %	The efficiency of the Inverter and motor controller.
Iqs*	The commanded value of the quadrature axis current.
Motor HP	The horsepower out of the motor.
Motor Temp deg F	The temperature of the stator in degrees Fahrenheit.
Motor Torque, in-lbs	The motor torque value after adjusting for test equipment friction losses.
One Phase Current Amps	The current into one phase of the motor.
One Phase Power (W)	The real power in one phase of the motor.
Single Phase PF	The power factor into one phase of the motor.
System Eff. %	The efficiency of the system from inverter input to motor output. Adjusted for test set inefficiencies.

Loss / Efficiency Test Notes

July 1993

- Loss/Efficiency measurements were made in accordance with the "40 HP Task Order System Test Plan" section 3.2.2
- Measurements were made at and around the operating point of maximum efficiency.
- The "Commanded Speed, RPM" is the motor speed commanded on the computer monitor. It does not directly represent the stator frequency since the stator frequency is dependent on the slip gain, and the values of I_{qs} and I_{ds} in addition to the commanded speed input from the computer.
- The "Dyno Torque" is the commanded value of load torque imposed by the dynamometer. Although a fixed torque value was commanded for a series of tests, the dyno load tended to vary with speed.
- All measurements have been adjusted to compensate for gear box frictional losses.

Loss/Eff 21 to 33 in-lbs

Commanded	fs-fr	Dyno	Motor	Motor	DC	DC	Single	One Phase	One Phase	Inv/Cont	System	Ids*	Iqs*	Motor	Gear	Dyno
Speed	FREQ	Speed	Torque	HP	Volts	Current	Phase	Power (W)	Current	Eff. %	Eff. %			Temp	Temp	Torque
RPM	Hz	RPM	In-lbs				PF		Amps					deg F	deg F	In-lbs
14000	680	3400	33.25	7.18	154	65.1	0.59	2290	62.4	68.5	53.4	40	64.8	160	105.8	102
14000	683.8	3419	33.25	7.22	154	64.3	0.62	2320	58	70.3	54.4	45	58	161	107.2	102
14000	684.8	3424	33	7.17	154	63	0.62	2350	56.2	72.7	55.1	48	48	162	109.4	102
14000	686.2	3431	33	7.19	154	63.4	0.61	2360	55.8	72.5	54.9	50	46	163	110.7	102
14000	689.6	3448	32.75	7.17	154	64.7	0.53	2530	57.5	76.2	53.7	60	31	168	111.7	102
14000	690.4	3452	32.5	7.12	154	66.7	0.46	2720	62.6	79.4	51.7	70	29	181	113.1	102
12000	578	2890	33.25	6.10	154.6	60.6	0.52	1966	65.4	63.0	48.6	40	67.6	142	92.8	100
12000	582.2	2911	33	6.10	154.6	58	0.57	1960	58.6	65.6	50.7	45	52.6	143	95.9	100
12000	585	2925	32.5	6.03	154.6	57.2	0.58	1967	56.1	66.7	50.9	48	45.1	143	98.9	99
12000	585.8	2929	32	5.95	154.6	56.6	0.57	1967	55.1	67.4	50.7	50	41.3	145	100.4	99
12000	589.2	2946	32	5.98	154.6	57.4	0.51	2140	57.2	72.3	50.3	60	30	148	101.9	99
12000	591	2955	32.75	6.14	154	60.4	0.45	2400	63.3	77.4	49.3	70	28	167	90.4	97
9000	428.8	2144	28.75	3.91	153	48.9	0.42	1350	62.6	54.1	39.0	35	63	142	97.7	88
9000	432.4	2162	28.75	3.95	153	46.9	0.49	1335	55.5	55.8	41.0	40	53	143	99	88
9000	436.2	2181	28.5	3.95	153	46.1	0.51	1356	52.5	57.7	41.7	45	45	143	99.5	88
9000	437.6	2188	28.25	3.92	153	45.9	0.5	1407	51.9	60.1	41.7	50	34	145	100	88
9000	441	2205	28.5	3.99	153	47	0.44	1541	55.8	64.3	41.4	60	26.3	148	101	89
9000	442.2	2211	28.75	4.03	154	50.5	0.4	1777	63	68.5	38.7	70	22.5	159	88.1	90
6000	281.8	1409	23	2.06	153.5	39.2	0.33	871	56.9	43.4	25.5	35	56.3	138	94	80
6000	285.2	1426	26	2.35	153.5	37.8	0.39	864	51.4	44.7	30.3	40	45	136	95.2	80
6000	287	1436	26	2.37	153.5	37.2	0.4	878	50.4	46.1	30.9	42	41	135	95.8	80
6000	288.4	1442	25.75	2.36	153.5	37	0.41	893	49.4	47.2	31.0	45	35.7	134	96	80
6000	290.4	1452	25.75	2.37	153.5	37.2	0.41	939	50.3	49.3	31.0	50	30	134	96.5	80
6000	292	1460	25.75	2.39	153.5	38.8	0.37	1059	55.4	53.3	29.9	60	22.5	134	96.9	80
6000	293.2	1466	26	2.42	154.5	41.22	0.33	1220	62.2	57.5	28.3	70	20.7	164	94.5	81

Loss/Eff 21 to 33 in-lbs

Commanded	fs-fr	Dyno	Motor	Motor	DC	DC	Single	One Phase	One Phase	Inv/Cont	System	Ids*	Iqs*	Motor	Gear	Dyno
Speed	FREQ	Speed	Torque	HP	Volts	Current	Phase	Power (W)	Current	Eff. %	Eff. %			Temp	Temp	Torque
RPM	Hz	RPM	In-lbs				PF		Amps					deg F	deg F	In-lbs
3000	132.4	662	21.5	0.90	153.5	31.5	0.2	453	53.4	28.1	13.9	35	56	136	88	70
3000	136.8	684	21.5	0.93	153.5	29.5	0.24	436	47.2	28.9	15.4	40	43	135	88.5	70
3000	138.2	691	21.5	0.94	153.5	29	0.25	430	45.7	29.0	15.8	42	37.6	128	91	70
3000	139.6	698	21.25	0.94	153.5	28.5	0.27	441	44.6	30.2	16.1	45	31.9	128	91.5	70
3000	137.6	688	21.25	0.93	153.5	29.1	0.28	477	45.3	32.0	15.5	45	26.3	128	91.6	70
3000	142.4	712	21.25	0.96	153.5	29.7	0.28	519	47.2	34.2	15.7	50	22.5	129	91.6	70
3000	143.8	719	21.25	0.97	153.5	31.9	0.26	620	54.2	38.0	14.8	60	18.8	132	91.9	70
3000	144.6	723	21.5	0.99	154.6	34.4	0.25	750	61.6	42.3	13.8	70	16.9	158	95.4	71

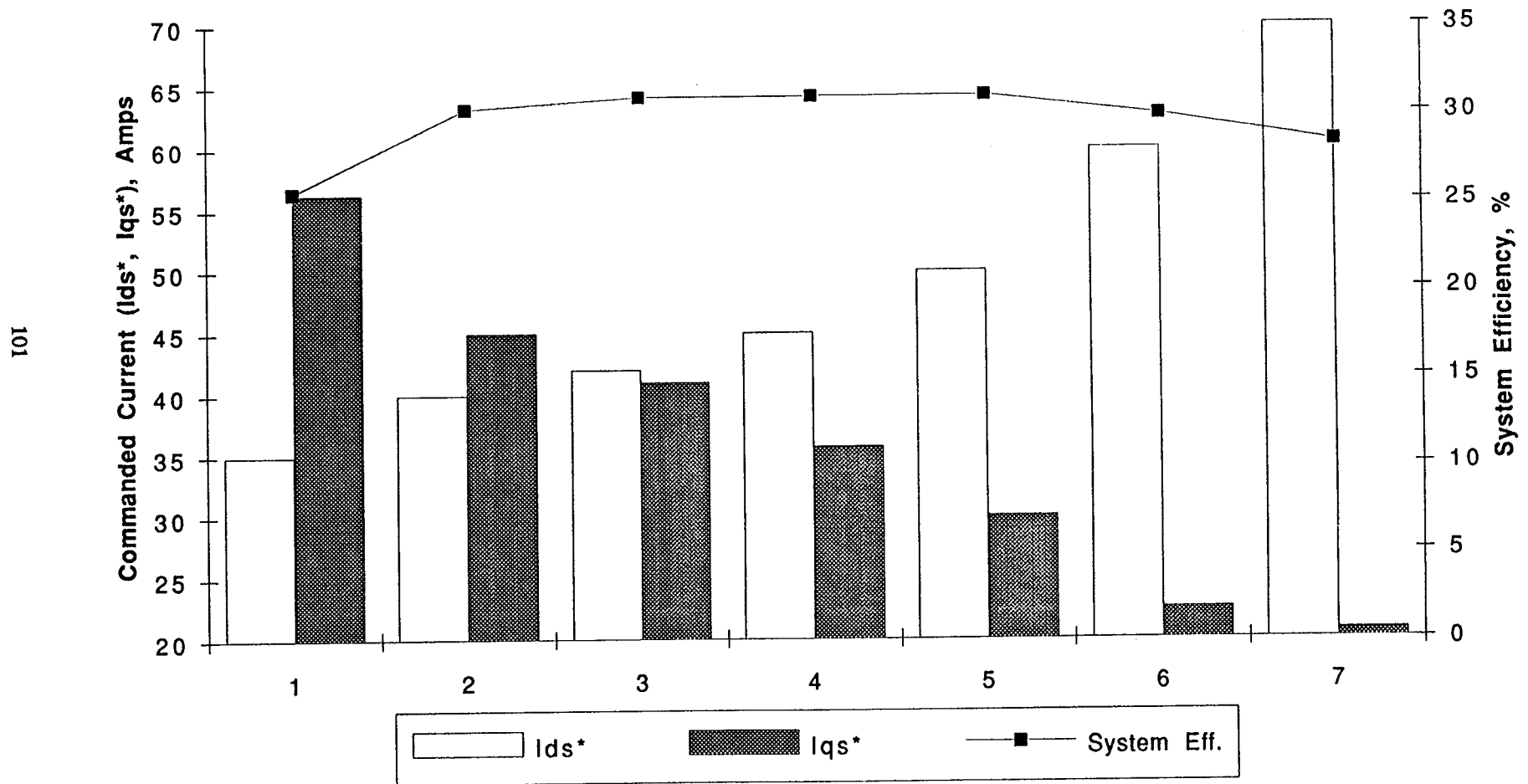
Loss/Eff 29 to 44 In-lbs

Commanded	fs-fr	Dyno	Motor	Motor	DC	DC	Single	One Phase	One Phase	Inv/Cont	System	Ids*	Iqs*	Motor	Gear	Dyno
Speed	FREQ	Speed	Torque	HP	Volts	Current	Phase	Power (W)	Current	Eff. %	Eff. %			Temp	Temp	Torque
RPM	Hz	RPM	In-lbs				PF		Amps					deg F	deg F	In-lbs
14000	680.0	3400	43.00	9.28	155	77.8	0.63	3040	65.2	75.6	57.4	50	59.2	181	113.0	144
14000	683.0	3415	43.75	9.48	155	77	0.63	3110	63.4	78.2	59.3	55	55.4	184	114.0	146
14000	685.0	3425	43.75	9.51	155	77.8	0.60	3170	63.1	78.9	58.8	60	46	188	115.0	146
14000	687.2	3436	44.25	9.65	155	78.8	0.54	3330	65.6	81.8	58.9	70	40	194	116.0	147
12000	578.8	2894	40.75	7.48	154.6	68.1	0.58	2410	65.7	68.7	53.0	45	64	174	110.0	137
12000	582.2	2911	41.25	7.62	154.6	66.7	0.60	2450	62.2	71.3	55.1	50	52.6	176	108.0	138
12000	586.2	2931	41.00	7.63	154.6	66.7	0.57	2600	61.4	75.6	55.2	60	43	179	106.6	137
12000	588.2	2941	41.25	7.70	154.6	68.7	0.50	2810	65.5	79.4	54.1	70	30	177	105.0	138
9000	430.0	2150	36.75	5.01	155.6	54.6	0.49	1710	63.2	60.4	44.0	45	64	151	100.6	123
9000	434.0	2170	37.25	5.13	155.6	53.5	0.52	1740	59.5	62.7	46.0	50	50.7	154	102.0	124
9000	437.4	2187	37.00	5.14	155.6	53.7	0.50	1860	59.4	66.8	45.9	60	37.6	157	103.0	123
9000	440.0	2200	37.25	5.20	155.6	55.8	0.44	2030	64.6	70.1	44.7	70	30	164	103.0	124
6000	280.0	1400	33.50	2.98	156	44.5	0.35	1097	63.3	47.4	32.0	40	62	144	100.5	112
6000	284.6	1423	33.75	3.05	156	42.4	0.40	1102	57.0	50.0	34.4	47	48	143	99.6	113
6000	286.4	1432	33.75	3.07	156	42.4	0.42	1120	55.8	50.8	34.6	50	43.2	144	99.2	113
6000	289.4	1447	34.00	3.12	156	43.2	0.40	1235	58.0	55.0	34.6	60	32	145	98.3	113
6000	291.2	1456	34.00	3.14	156	45.1	0.37	1361	63.4	58.0	33.3	70	26	143	97.9	113
3000	134.0	670	28.25	1.20	156	33.9	0.22	553	55.9	31.4	16.9	40	52.6	120	98.3	100
3000	137.2	686	28.25	1.23	156	32.5	0.26	561	51.6	33.2	18.1	45	41.3	123	97.8	100
3000	139.8	699	28.50	1.26	156	32.9	0.27	596	51.4	34.8	18.4	50	32	125	97.7	101
3000	141.2	706	28.75	1.29	156	34.1	0.27	689	55.8	38.9	18.1	60	24.4	128	97.6	101
3000	143.2	716	28.75	1.31	156	36.2	0.26	808	62.6	42.9	17.3	70	20.7	132	97.6	101

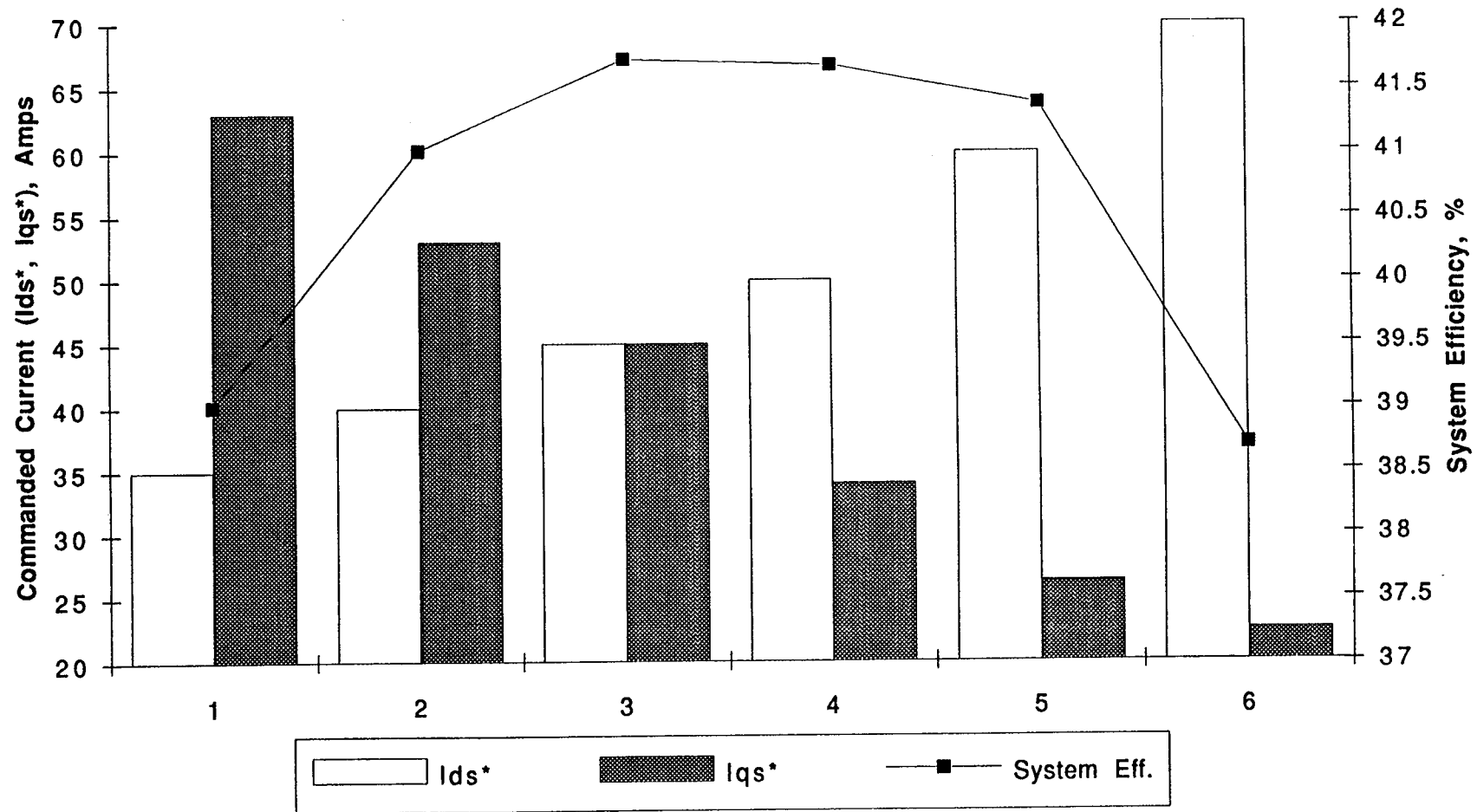
Loss/Eff 63 to 70 in-lbs

Commanded	fs-fr	Dyno	Motor	Motor	DC	DC	Single	One Phase	One Phase	Inv/Cont	System	Ids*	Iqs*	Motor	Gear	Dyno
Speed	FREQ	Speed	Torque	HP	Volts	Current	Phase	Power (W)	Current	Eff. %	Eff. %			Temp	Temp	Torque
RPM	Hz	RPM	In-lbs				PF		Amps					deg F	deg F	In-lbs
14000	662.4	3312	70	14.71	161.8	106.9	0.63	4730	80.6	82.0	63.5	70	70	190	103.5	247
14000	678.2	3391	65	13.99	159	101	0.62	4550	77.3	85.0	65.0	70	68.6	199	99.7	226
12000	581	2905	63.5	11.71	160	90.5	0.59	3880	74.9	80.4	60.3	70	56.3	208	99.7	222

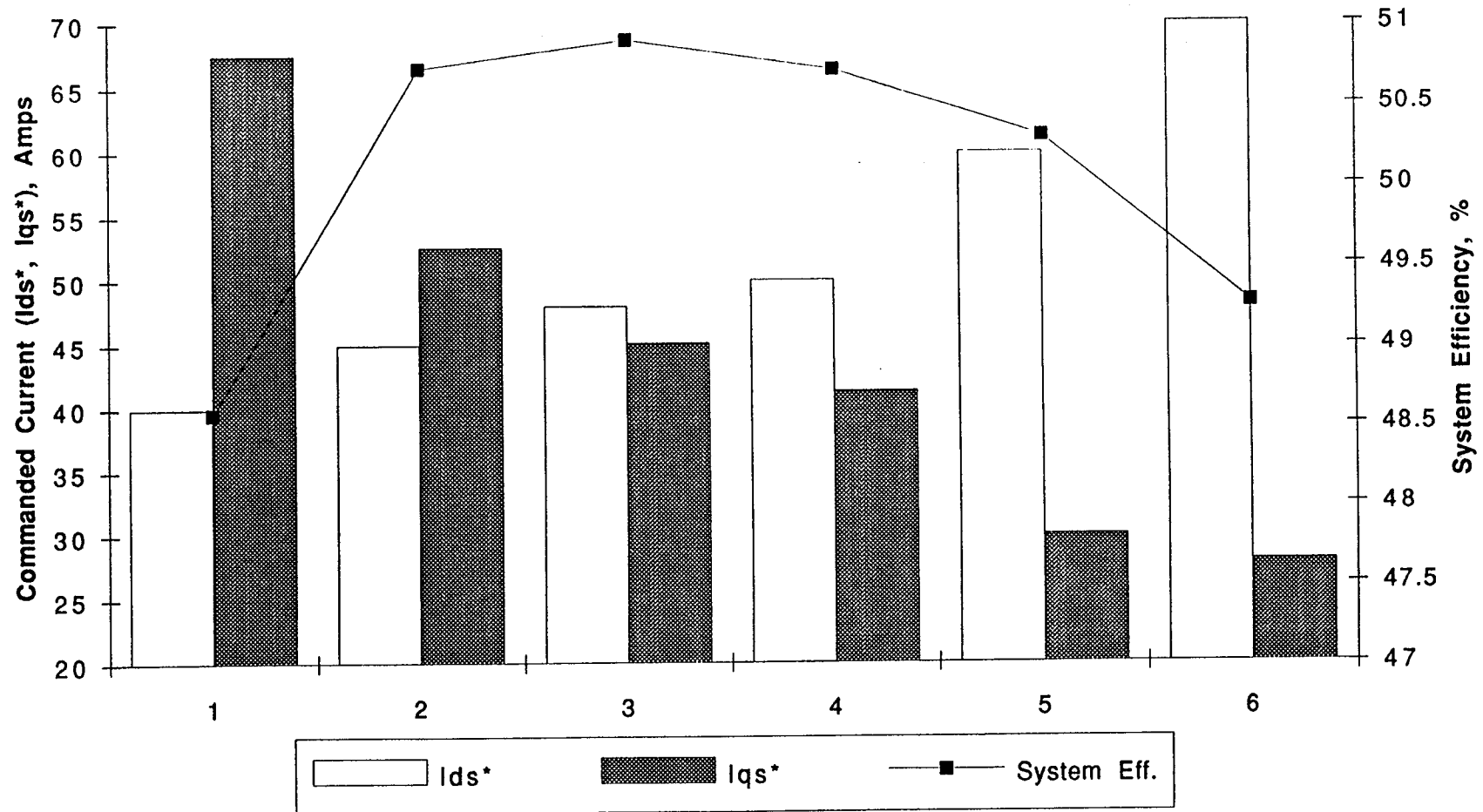
System Efficiency vs I_{ds}^* & I_{qs}^* (6000 RPM, 26 in-lbs)



System Efficiency vs I_{ds}^* & I_{qs}^* (9000 RPM, 29 in-lbs)

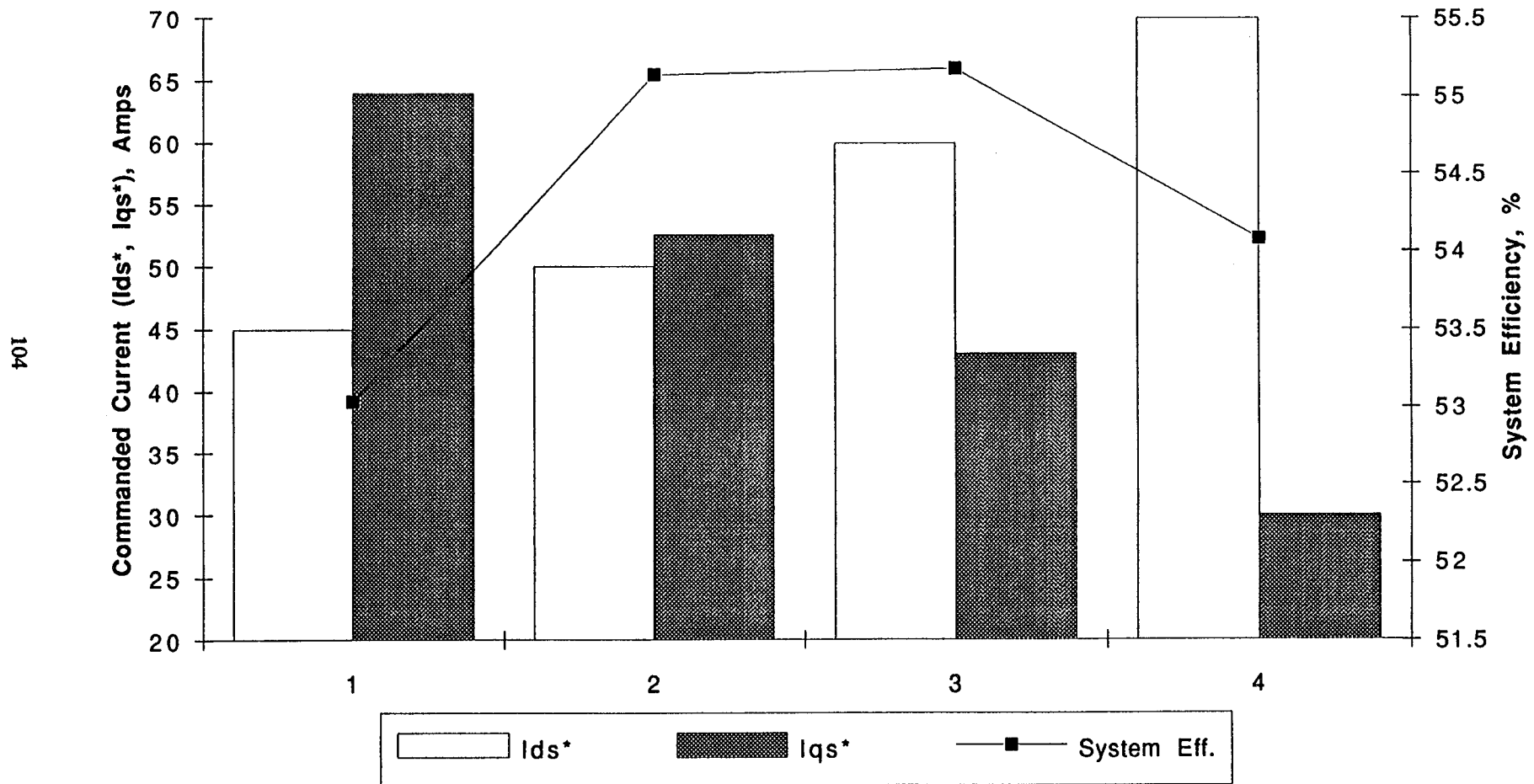


System Efficiency vs I_{ds}^* & I_{qs}^* (12000 RPM, 33 in-lbs)



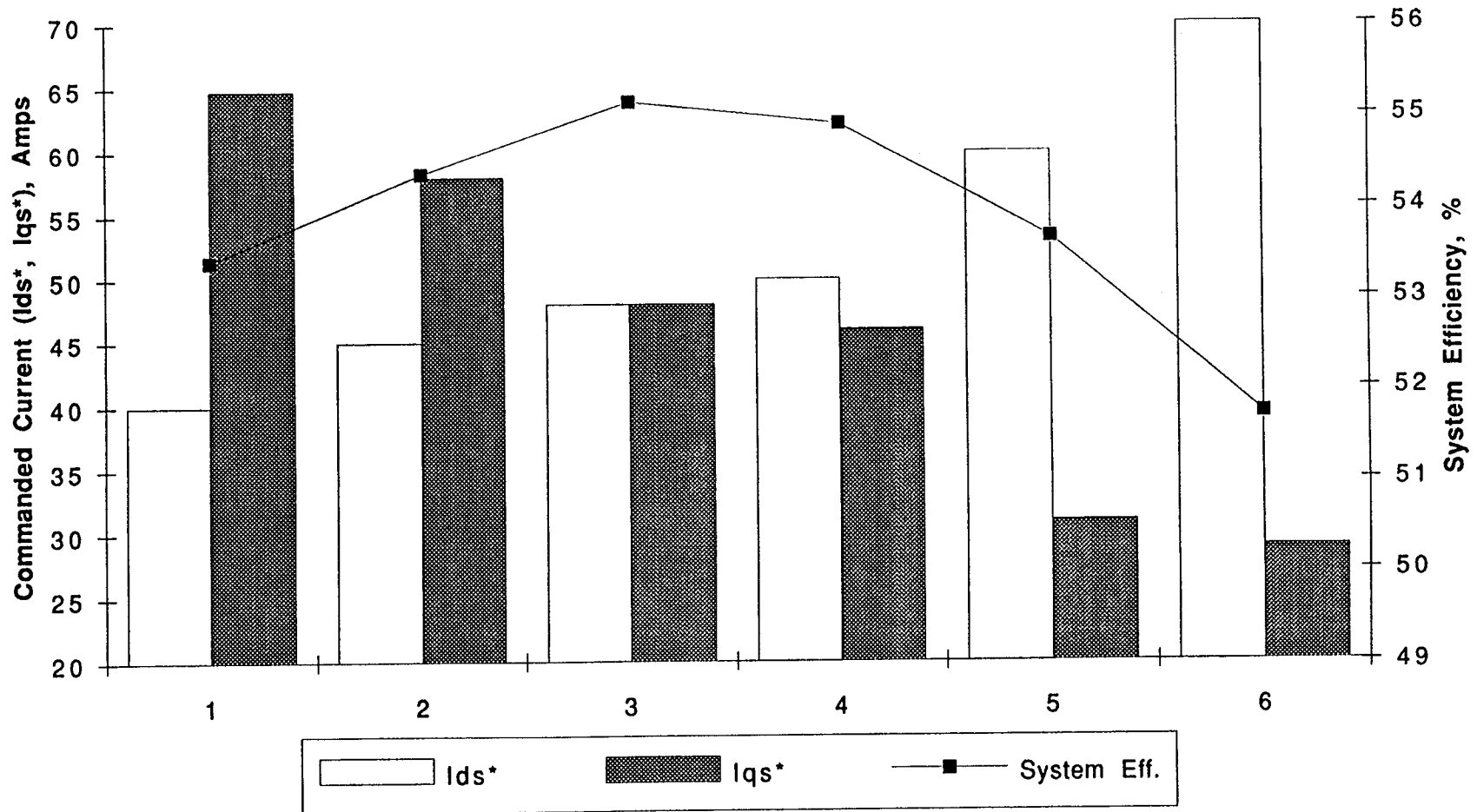
Sys Eff. I_{ds}/I_{qs} 2K, 41 in-lbs

System Efficiency vs I_{ds}^* & I_{qs}^* (12000 RPM, 41 in-lbs)

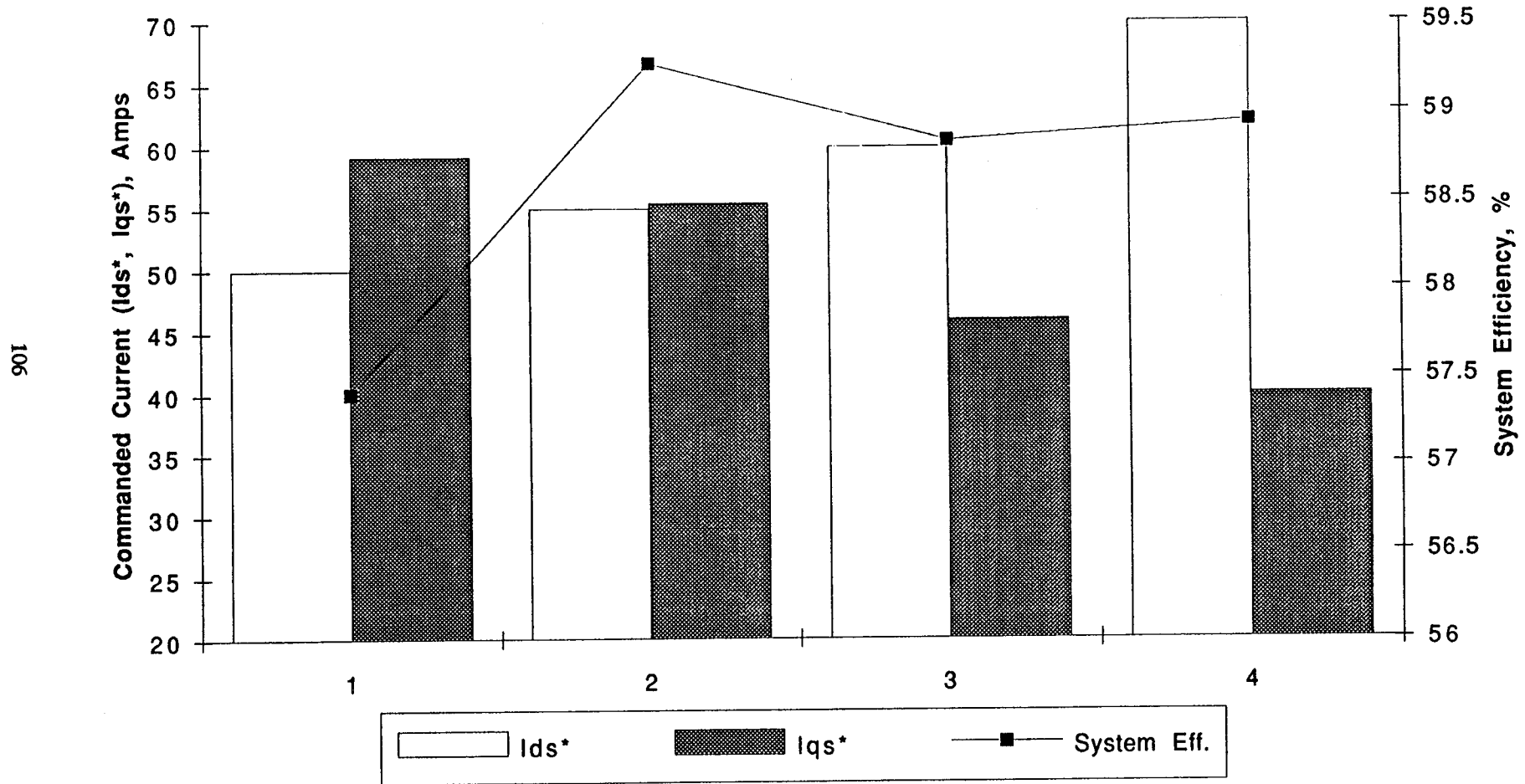


Sys Eff. I_{ds}/I_{qs} .4K, 33 in-lbs

System Efficiency vs I_{ds}^* & I_{qs}^* (14000 RPM, 33 in-lbs)



System Efficiency vs I_{ds}^* & I_{qs}^* (14000 RPM, 44 in-lbs)



APPENDIX H

Worst Case Error Analysis

<u>Section</u>	<u>Subject</u>
1	Core Loss and Magnetizing Inductance Error; 730 Hz & 55 A/Phase
2	Core Loss and Magnetizing Inductance Error; 150 Hz & 28 A/Phase
3	Rotor Resistance and Leakage Inductance; 730 Hz & 75 A/Phase
4	System Efficiency Error 13,800 RPM & 70 A/Phase
5	Power Stage Efficiency Error 13,800 RPM & 70 A/Phase
6	Motor Efficiency Error 13,800 RPM & 72 A/Phase

Worst Case Error Analysis

Motor Parameters

- ① Determine errors in Core Loss (R_m) and Magnetizing Inductance (L_m)

Data Point: Frequency = 730Hz No Load motor Test

$$\text{Harmonic Voltage per } \phi = 92.2V \pm 2V$$

$$\text{Fundamental Voltage per } \phi = 85.1V \pm 5\%$$

$$\text{Current per phase} = 54.9A \pm 3.1A$$

$$\text{Error in power measurement} = \pm 310VA$$

$$\text{Error in P.F. measurement} = \pm 4\% \quad PF = 0.74$$

(A) Core Loss

$$R_m = \frac{V^2}{P_{\text{real}}} \quad R_{m \text{ max}} = \frac{(92.2 + 2)^2}{(92.2 \times 54.9 - 310)(0.74 \times 0.96)}$$

$$\text{where } P_{\text{real}} = P_{\text{apparent}} \times PF$$

$$R_{m \text{ max}} = 13.9 \Omega$$

$$R_{m \text{ min}} = \frac{(90.2)^2}{(5063 + 310)(0.74 \times 1.04)} = 10.4 \Omega$$

So: $R_m (12.2 \Omega)$ core loss

→ 13.9 Ω max (+13.9%)

→ 10.4 Ω min (-14.8%)

Power Accuracy measured = 695W

→ 782W (+12.6%)

→ 639W (-8.1%)

①

(B) magnetizing Inductance

$$Z_{nl} = \frac{V_{fund.}}{I}$$

$$Z_{nl \max} = \frac{89.4}{51.8} = 1.73 \Omega$$

$$Z_{nl \min} = \frac{80.8}{58.0} = 1.39 \Omega$$

$$X_m = \left[\frac{1}{Z_{nl}} - \frac{1}{R_m} \right]^{-1}$$

$$X_{m \max} = 2.06$$

$$X_{m \min} = 1.54$$

$$L_m = \frac{X_m}{2\pi f}$$

$$L_{m \max} = 4.50 \times 10^{-4}$$

$$L_{m \min} = 3.37 \times 10^{-4}$$

$L_m (3.87 \times 10^{-4})$	$\begin{cases} 4.50 \times 10^{-4} \max (+16.3\%) \\ 3.37 \times 10^{-4} \min (-12.9\%) \end{cases}$
-----------------------------	------------------------------------------------------------------------------------------------------

- ② Determine R_m and L_m at low frequency and low voltage (High error data point)

Data Point:

Frequency = 150 Hz No Load motor Test

Harmonic Voltage per ϕ = $23V \pm 0.6V$

Fundamental Voltage per ϕ = $9.6V \pm 5\%$

Current per ϕ = $28A \pm 3.1A$

Error in power measurement = 93 VA

Error in P.F. measurement = $\pm 4\%$ PF = 0.15

(A) Core Loss

$$R_m \max = \frac{(23.6)^2}{(644 - 93)(0.15 \times 0.96)} = 7.0 \Omega$$

$$R_m \min = \frac{(22.4)^2}{(644 + 93)(0.15 \times 1.04)} = 4.4 \Omega$$

$R_m (5.34)$	$\nearrow 7.0 \Omega \max (+31.1\%)$ $\searrow 4.4 \Omega \min (-17.6\%)$
--------------	------------------------------------------------------------------------------

power accuracy $P_{real} = 99W$

$\nearrow 115W \max (+16.2\%)$
$\searrow 79.3W \min (-19.9\%)$

②

(B) magnetizing Inductance

$$Z_{nl} = \frac{V_{fund}}{I} \quad Z_{nl \max} = \frac{(9.6)(1.05)}{(28-3.1)}$$

$$Z_{nl \max} = 0.40 \Omega$$

$$Z_{nl \min} = \frac{(9.6)(0.95)}{(28+3.1)} = 0.29 \Omega$$

$$X_{m \max} = \left[\frac{1}{0.29} - \frac{1}{4.4} \right]^{-1} = 0.31$$

$$X_{m \min} = \left[\frac{1}{0.40} - \frac{1}{4.4} \right]^{-1} = 0.44$$

$L_m (3.89 E-4)$	$\nearrow 4.67 E-4 \text{ }_{\max} (+20.1\%)$
	$\searrow 3.29 E-4 \text{ }_{\min} (-15.4\%)$

③ Rotor Resistance (R_r) and Leakage Inductance (L_{eq})

Data Point:

$$\text{Frequency} = 736 \text{ Hz}$$

$$R_s = 0.051 \pm 0.002 \Omega$$

$$\text{Harmonic Voltage per } \phi = 55.8 \text{ V} \pm 1.2 \text{ V}$$

$$\text{Fundamental Voltage per } \phi = 19 \text{ V} \pm 5\%$$

$$\text{Current per } \phi = 75.3 \text{ A} \pm 3.1$$

$$\text{Error in power measurement} = \pm 186 \text{ VA}$$

$$\text{Error in power factor} = \pm 4\% \quad \text{PF} = 0.11$$

(A) Rotor Resistance

$$R_{eq} = \frac{\text{Real Power}}{I^2}$$

$$R_{eq \text{ max}} = \frac{[(55.8 \times 75.3) + 186][0.11 \times 1.04]}{(75.3 - 3.1)^2}$$

$$R_{eq \text{ max}} = 9.63 \text{ E-2}$$

$$R_{eq \text{ min}} = \frac{[55.8 \times 75.3 - 186][0.11 \times 0.96]}{(75.3 + 3.1)^2}$$

$$R_{eq \text{ min}} = 6.9 \text{ E-2}$$

$$R_r = R_{eq} - R_s$$

	$R_r (3.08 \text{ E-2})$	4.53 E-2 max (+47%)
		1.8 E-2 min (-42%)
Power	464 W	502 max (+8.2\%) 424 min (-8.6\%)

③

(B) Leakage Inductance

$$Z_{br} = \frac{V_{\text{fundamental}}}{I}$$

$$Z_{br \text{ max}} = \frac{19.95}{72.2} = 0.28 \Omega \text{ max}$$

$$Z_{br \text{ min}} = \frac{18.05}{78.4} = 0.23 \Omega \text{ min}$$

$$X_L = \sqrt{Z_{br}^2 - R_{eq}^2}$$

$$X_{L \text{ max}} = \sqrt{(0.28)^2 - (6.9 \text{ E-} 2)^2} = 0.27$$

$$X_{L \text{ min}} = \sqrt{(0.23)^2 - (9.63 \text{ E-} 2)^2} = 0.21$$

$$L_{eq} = \frac{X_L}{2\pi f}$$

$$L_{eq \text{ max}} = 5.89 \text{ E-} 5 \text{ Henries}$$

$$L_{eq \text{ min}} = 4.58 \text{ E-} 5 \text{ Henries}$$

$L_{eq} (5.21 \text{ E-} 5) \begin{cases} \nearrow 5.89 \text{ E-} 5 (+13.1\%) \\ \searrow 4.58 \text{ E-} 5 (-12.1\%) \end{cases}$

④ System Efficiency Error

Determine error in system efficiency calculation

Data Point:

$$\text{Frequency} = 700 \text{ Hz}$$

$$\text{Dyno Speed} = 3450 \text{ RPM}$$

$$\text{Current per phase} = 68.9 \text{ A} \pm 3.1 \text{ A}$$

$$\begin{aligned} \text{DC Input Voltage} &= 178 \text{ V} \\ &\pm (0.0002 \times 178) + (0.00008 \times 2000) \\ &= \pm 0.20 \text{ V} \end{aligned}$$

$$\begin{aligned} \text{DC current} &= 41 \text{ mV} \\ \text{(mv reading across shunt resistor)} &\pm (0.0002 \times 41 \text{ mV}) + (0.00008 \times 2000 \text{ mV}) \\ &= \pm 0.024 \text{ mV} \end{aligned}$$

$$\text{Motor Torque} = 53.75 \text{ in-lbs} \pm 3 \text{ in-lbs}$$

$$\text{System eff \%} = \frac{\text{power out}}{\text{power in}} \times 100$$

$$\text{DC Power In} = V_{DC} \cdot I_{DC}$$

$$\text{DC Power max} = \frac{(178.2) \cdot (41.024)}{0.0004949 \text{ (shunt value)}}$$

$$\text{DC Power max} = 14771 \text{ W}$$

④ (continued)

$$\text{DC power min} = \frac{(177.8)(40.98)}{0.0004149} = 14723 \text{ W}$$

$$\text{motor Power (HP)} = \frac{(\text{motor Torque})(\text{motor RPM})}{5250 \cdot 12} \leftarrow \text{conversion constants}$$

$$\text{motor Power max (HP)} = \frac{(53.75 \text{ in-lbs} + 3 \text{ in-lbs})(3450 \cdot 4)}{5252 \cdot 12}$$

$$\text{motor HP}_{\text{max}} = 12.43$$

$$\text{motor HP}_{\text{min}} = \frac{(53.75 \text{ in-lbs} - 3 \text{ in-lbs})(3450 \cdot 4)}{5252 \cdot 12}$$

$$\text{motor HP}_{\text{min}} = 11.11$$

$$\begin{aligned} \text{System eff. max} &= \frac{(12.43 \text{ HP})(746 \text{ W/HP})}{14723 \text{ (W)}} \times 100 \\ &= 63\% \end{aligned}$$

$$\text{System eff. min} = \frac{(11.11 \text{ HP})(746 \text{ W/HP})}{14771 \text{ (W)}}$$

$$= 56\%$$

System eff 59% $\begin{cases} \nearrow 63\% \text{ max} \\ \searrow 56\% \text{ min} \end{cases}$

Power Stage Efficiency Error

⑤

Determine error in Power Stage Efficiency Error

Data Point :

$$\begin{aligned} \text{Frequency} &= 700 \text{ Hz} \\ \text{Dyno Speed} &= 3450 \text{ RPM} \\ \text{Motor PF} &= 0.63 \pm 0.5\% \end{aligned}$$

$$\left. \begin{aligned} \text{Current per phase} &= 68.4 \text{ A} \pm 3.1 \text{ A} \\ \text{Voltage per phase} &= 87.6 \text{ V} \pm 2.0 \text{ V} \end{aligned} \right\} \text{Apparent Power} = 6036 \text{ VA} \pm 310 \text{ VA}$$

$$\begin{aligned} \text{Real Power out (inverter)} &= 11930 \text{ W} \pm (1860 \text{ VA} \times \text{PF}) \\ \text{Power Factor out (inverter)} &= 0.54 \pm 0.5\% \end{aligned}$$

$$\begin{aligned} 20 \text{ kHz Voltage} &= 350 \text{ V} \pm 1.9 \text{ V} \\ \text{Apparent Power out (inverter)} &= 21770 \text{ VA} \pm 1860 \text{ VA} \\ 20 \text{ kHz current out (inverter)} &= 62.2 \text{ A} \pm 3.1 \text{ A} \end{aligned}$$

$$\text{Real Power (inverter max)} = (\text{Apparent power} + 1860 \text{ VA}) (\text{PF} + 0.5\%)$$

$$= (21770 + 1860) (-0.54 \pm 1.005)$$

$$= 12824 \text{ W} (+7.5\%)$$

$$\begin{aligned} \text{Real Power (inverter min)} &= (\text{Apparent power} - 1860) (\text{PF} - 0.5\%) \\ &= 10698 \text{ W} (-10.3\%) \end{aligned}$$

⑤ (continued)

$$\text{Power Stage Out (Per phase)} = (\text{Apparatus Power} \pm \text{error})(\text{PF} \pm \text{error})$$

$$\begin{aligned}\text{Power stage Out (per phase) max} &= (6036 + 310)(0.63 \times 1.005) \\ &= 4018 \text{ W/phase } (+6.3\%)\end{aligned}$$

$$\begin{aligned}\text{Power Stage Out (per phase) min} &= (6036 - 310)(0.63 \times 0.995) \\ &= 3589 \text{ W/phase } (-5.1\%)\end{aligned}$$

$$\text{Power Stage Eff. \%} = \frac{\text{Power Out Motor}}{\text{Power in P.S.}} \times 100$$

$$\begin{aligned}\text{Power stage Eff max} &= \frac{4018 \times 3}{10698} \times 100 \\ &= 113\%\end{aligned}$$

↖ 3 phases

$$\begin{aligned}\text{Power stage Eff min} &= \frac{3589 \times 3}{12824} \times 100 \\ &= 84\%\end{aligned}$$

Power Stage Eff. (87%) ↗ 100% max
↘ 84% min

⑥ Motor Efficiency Errors

Determine the error in the motor efficiency calculations

Data Point:

$$\text{Frequency} = 700 \text{ Hz}$$

$$\text{Dyna speed} = 3460 \text{ RPM} ; \text{ motor speed} = 13,600 \text{ RPM}$$

$$\text{Apparent Power (per phase)} = 4895 \text{ VA} \pm 310 \text{ VA}$$

$$\text{Power Factor} = 0.61 \pm 0.5\%$$

$$\text{Motor Torque} = 44.5 \text{ in-lbs} \pm 3 \text{ in-lbs}$$

$$\text{Single phase motor Input Power} = [\text{Apparent Power} \pm \text{error}] [\text{PF} \pm \text{error}]$$

$$\begin{aligned} \text{Motor Power}_{\text{max}} &= (4895 + 310)(0.61 \times 1.005) \\ &= 3191 \text{ W/d} \end{aligned}$$

$$\begin{aligned} \text{Motor Power}_{\text{min}} &= (4895 - 310)(0.61 \times 0.995) \\ &= 2783 \text{ W/d} \end{aligned}$$

$$\text{Motor Power Output} = \frac{(\text{motor torque} \pm \text{torque error})(\text{RPM})}{(12)(5252)}$$

$$\text{motor power max} = 10.25 \text{ HP}$$

$$\text{motor power min} = 8.96 \text{ HP}$$

⑥ (continued)

$$\begin{aligned}\text{maximum efficiency}_{\text{motor}} &= \frac{\text{motor power out}_{\text{max}}}{\text{motor power in}_{\text{min}}} \times 100 \\ &= \frac{(10.25 \text{ HP})(746 \text{ W/HP})}{2783 \text{ W}/\phi \times 3\phi} \\ &= 92\%\end{aligned}$$

$$\begin{aligned}\text{minimum efficiency}_{\text{motor}} &= \frac{(8.96 \text{ HP})(746 \text{ W/HP})}{(3191 \text{ W}/\phi)(3\phi)} \\ &= 70\%\end{aligned}$$

motor efficiency (80%) $\begin{cases} 92\% \text{ max} \\ 70\% \text{ min} \end{cases}$

APPENDIX I

No Load Actuator Test Procedure

The following test procedure is copied from the Task 13 Statement Of Work.

ATTACHMENT A

FREQUENCY RESPONSE TEST PROCEDURE

Install the actuator in test stand.

Connect necessary instrumentation to EMA.

Perform the following steps for each test case.

 Apply specified sinusoidal command for a ten cycle minimum.

 Determine gain and phase shift.

 Plot position vs. command on X-Y plot.

Obtain strip chart data.

TEST CASE	FREQUENCY (HZ)	AMPLITUDE (INCHES) ZERO TO PEAK
1	0.05	1,2 AND 5.0
2	0.25	0.1,0.25 AND 0.5
3	0.5	0.1,0.25 AND 0.5
4	1.0	0.1,0.25 AND 0.5
5	2.0	0.1,0.25 AND 0.5
6	3.0	0.1,0.25 AND 0.5
7	4.0	0.1,0.25 AND 0.5
8	5.0	0.1,0.25 AND 0.5
9	6.0	0.1,0.25 AND 0.5

ATTACHMENT A

STEP RESPONSE TEST PROCEDURE

Install actuator in test stand.

Connect all necessary instrumentation to the EMA.

For each test case, perform the following:

Command actuator to zero inches.

Apply square wave of specified amplitude; at least 5 cycle duration with 3 seconds between steps.

Obtain strip chart data.

TEST CASE	STEP COMMAND (INCHES) PEAK TO PEAK
1	0.5
2	1.0
3	2.0
4	4.0
5	6.0
6	8.0
7	10.0
8	11.0

APPENDIX J

No Load Actuator Test Data

The no load test data was recorded under the following conditions:

- $K_{pp} = 14.3$ and $K_{pr} = 1.53$ unless otherwise noted.
- K_{pp} is noted as K_p in the data.
- Command and Position scales are equal on the strip charts unless otherwise noted.

$\phi 1104$

5 mm/522

41304

0.50.21.7.7

7/17/1907

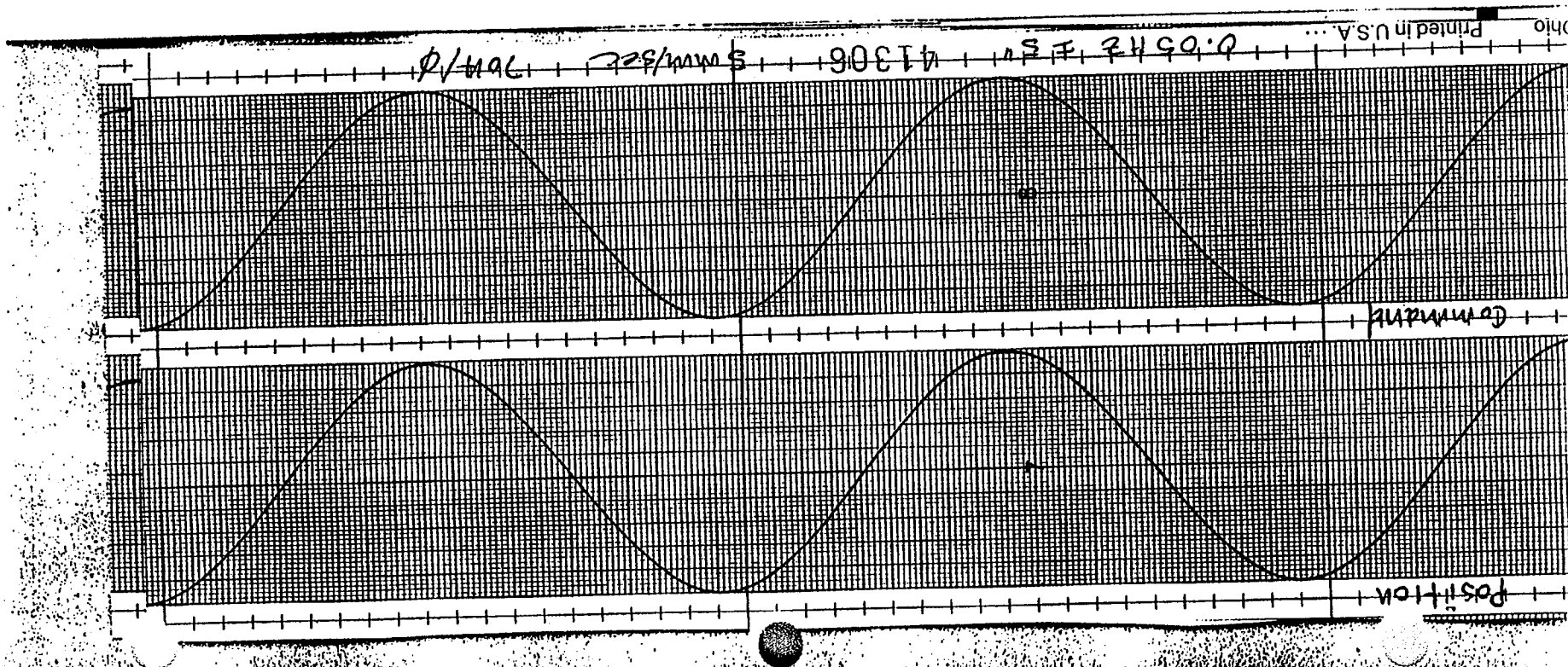
Position

Ø/6104.

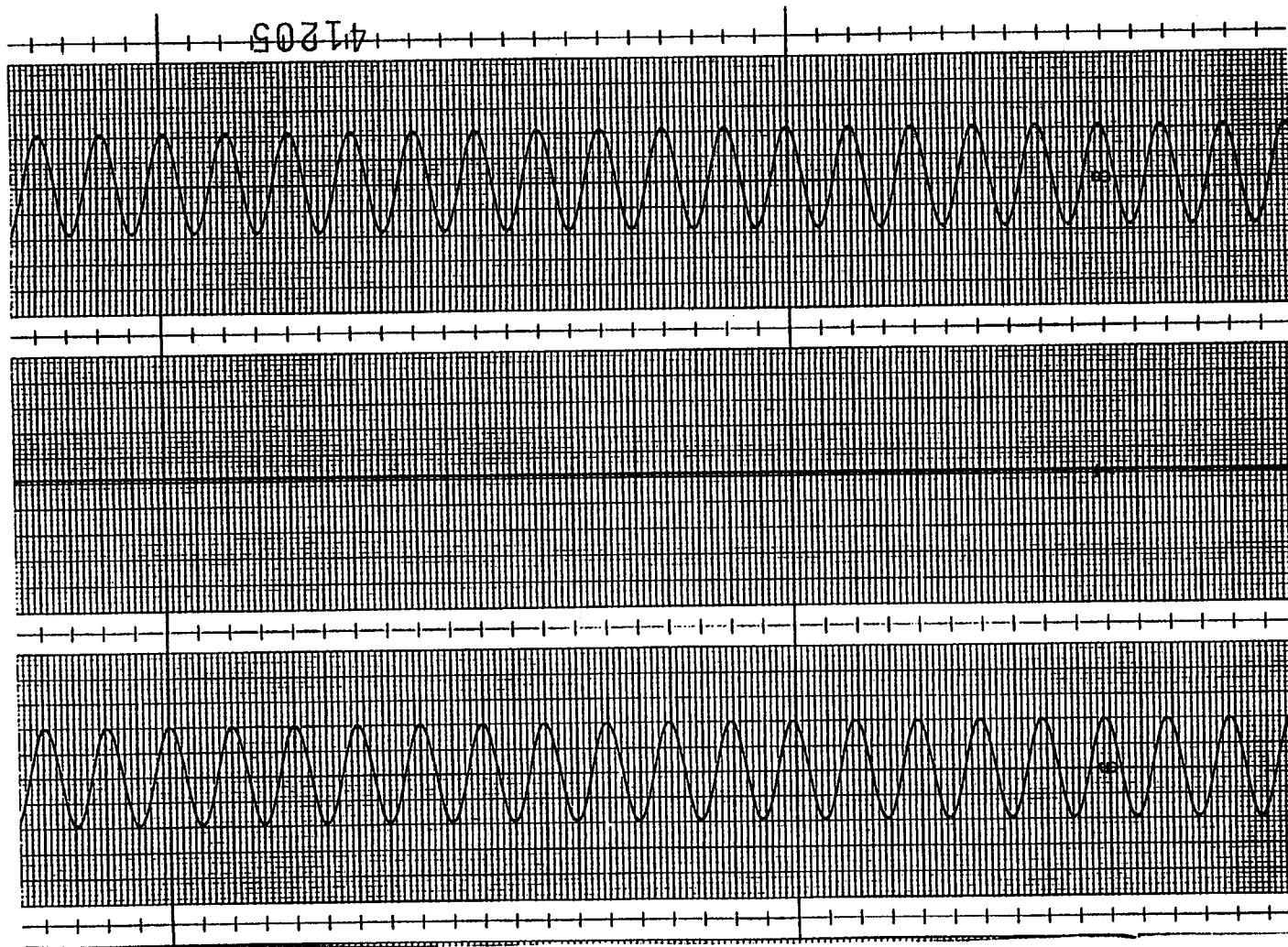
205/11111111

0.17 715010

Commanzi



0.25 Hz \pm 0.1 inch 474107 2.5 mm/sec



Command

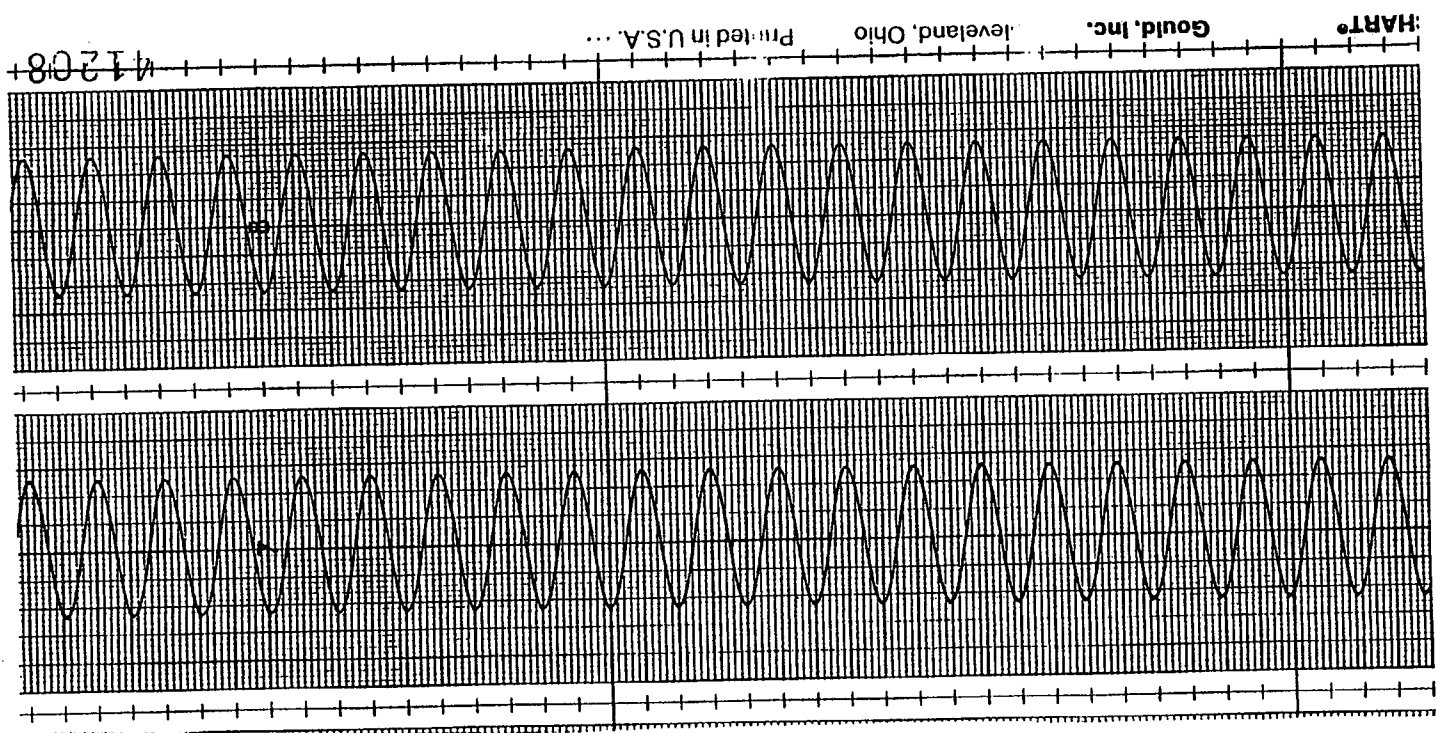
Position

Ch-21-8

Command

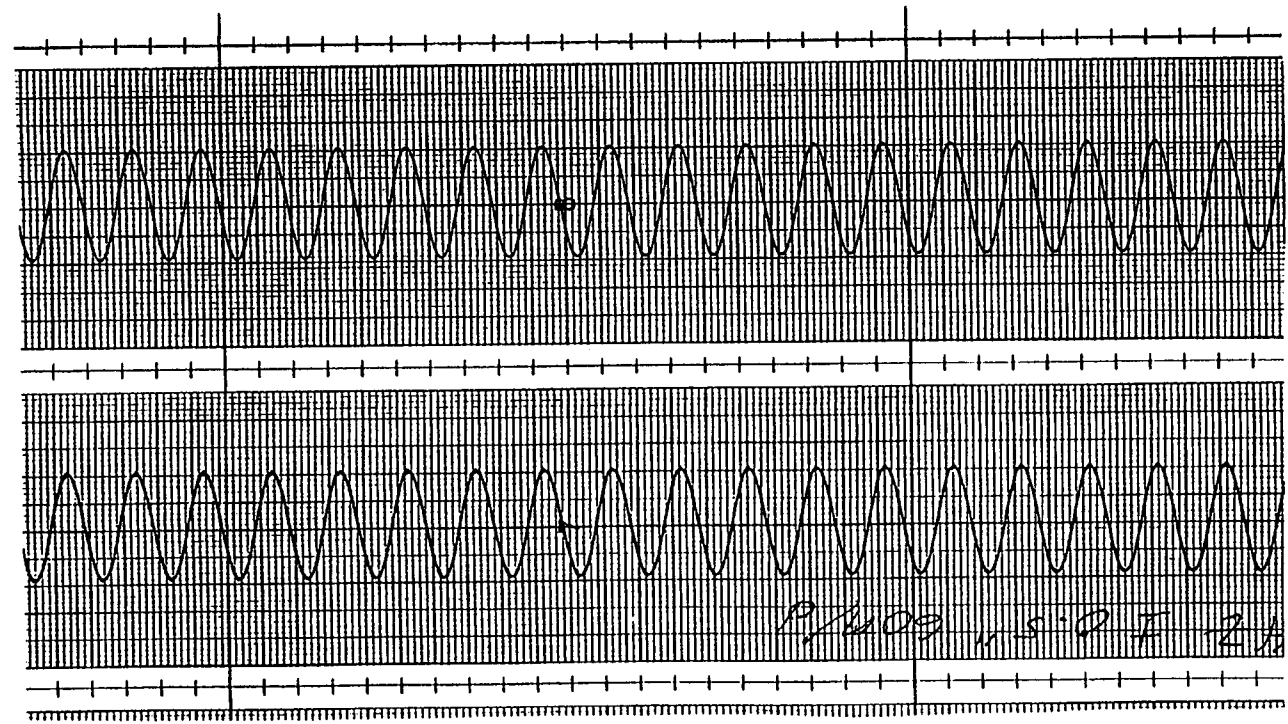
Position

0.25 Hz \pm 0.25 inch 600/phi 2.5 mm/sec



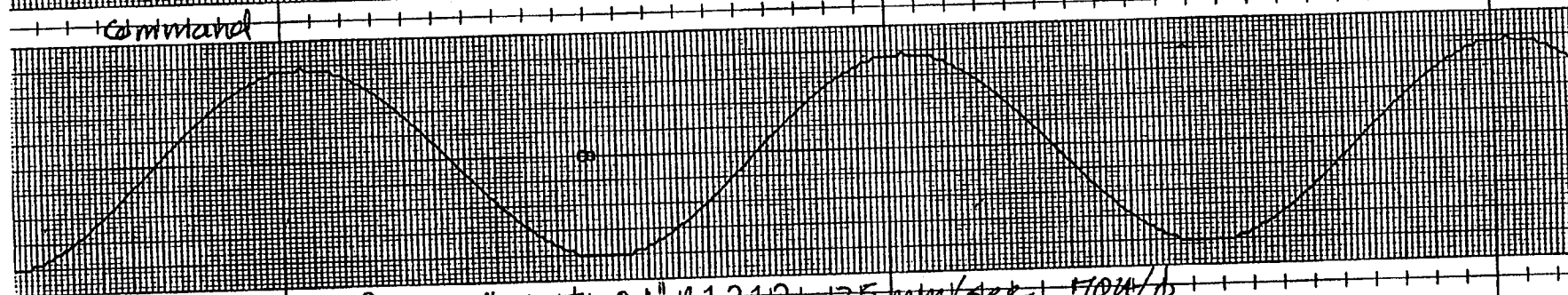
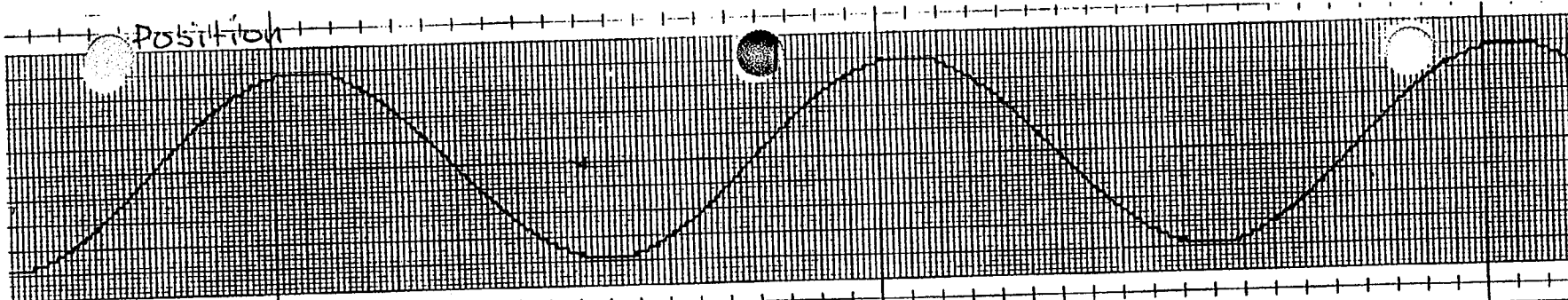
Command

Position

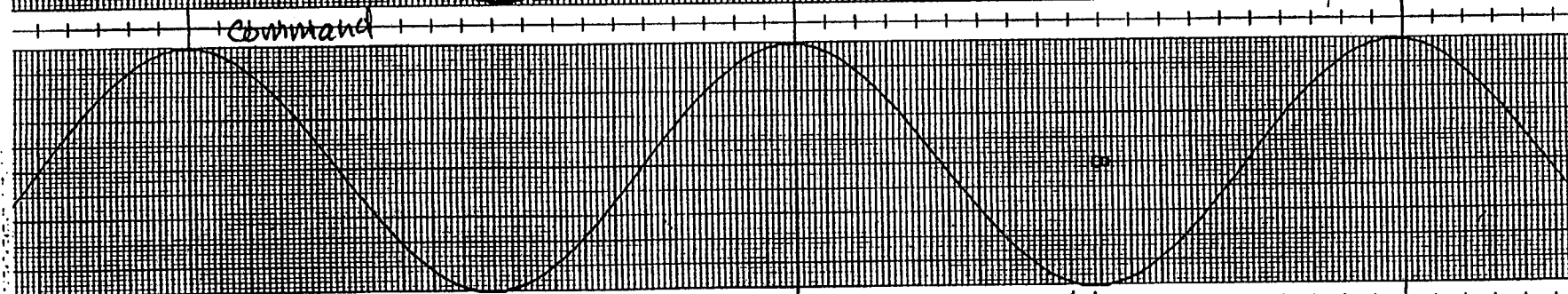
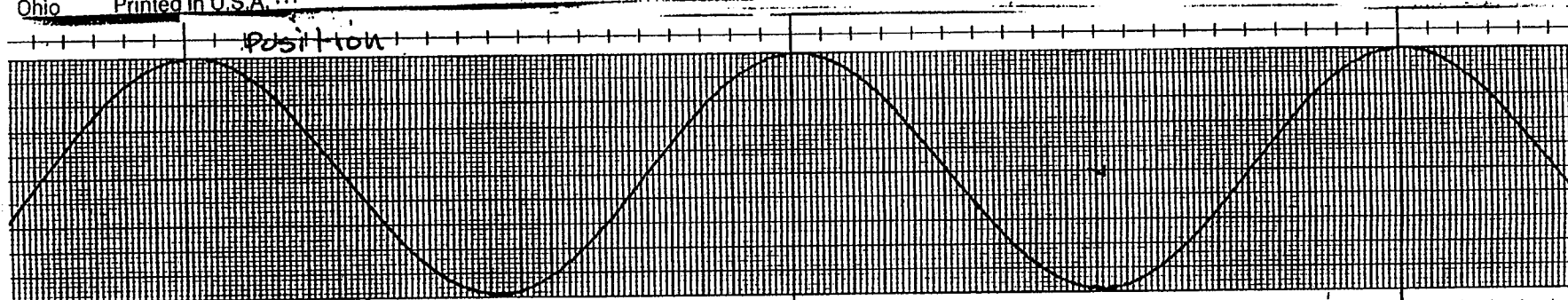


0.25 Hz \pm 0.5" ϕ 1409 2.5 mm/sec

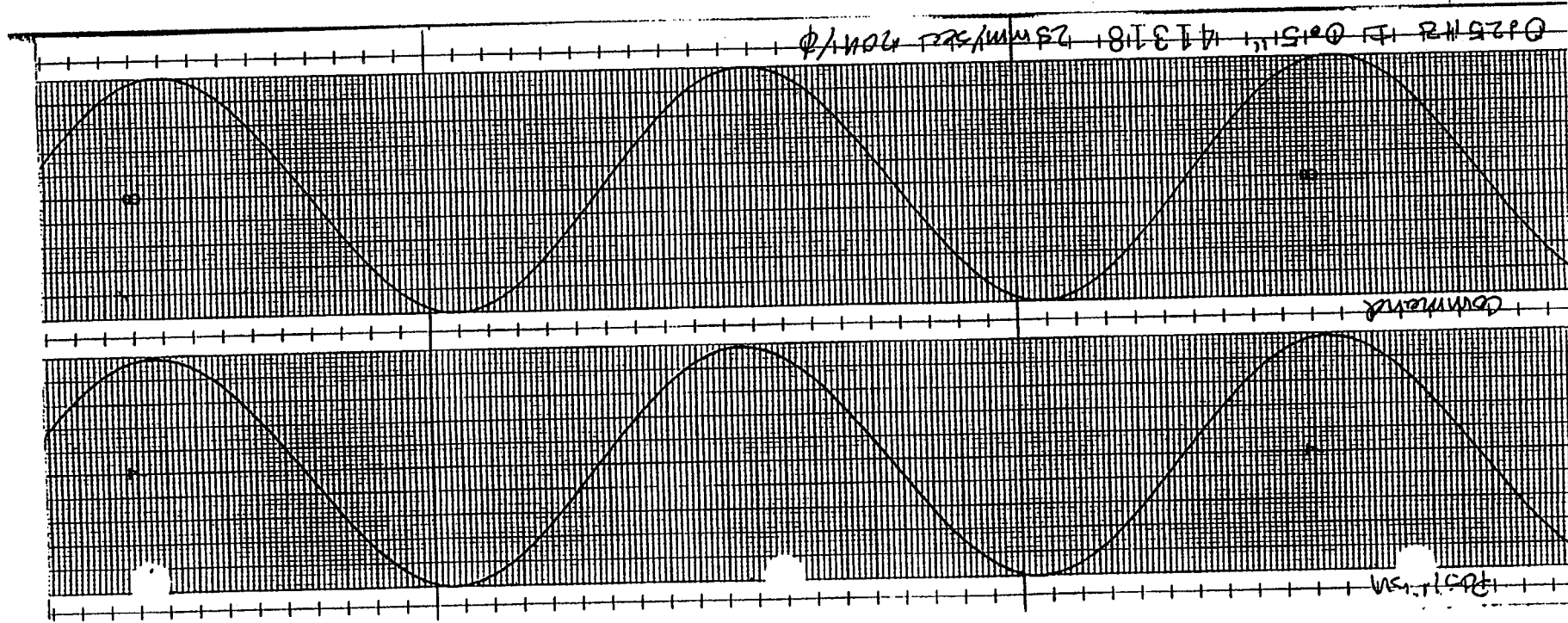
0.25 Hz \pm 0.5" ϕ 1409



Ohio Printed in U.S.A. 0.25 Hz 0.1" 41312 25 mm/sec 170A/φ



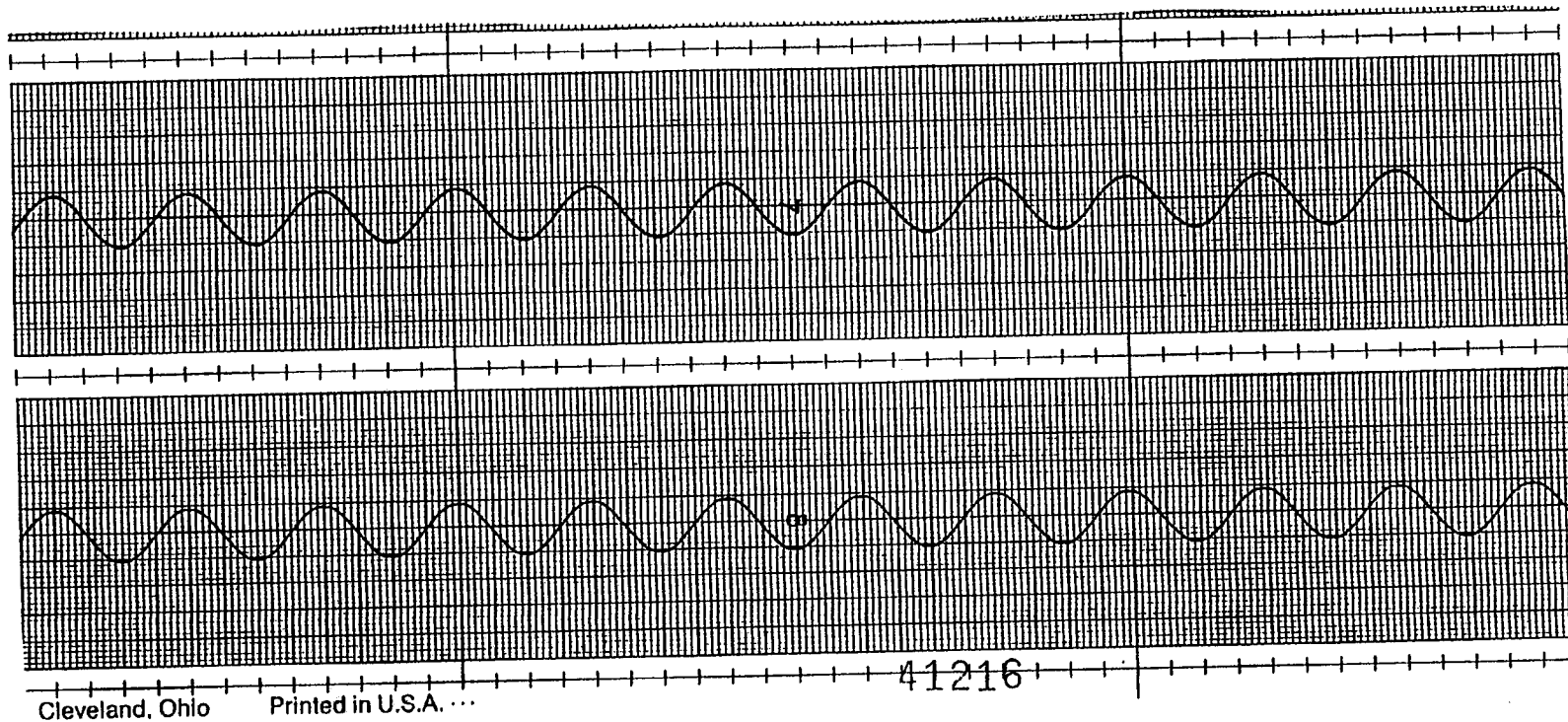
0.25 Hz 0.25" 41315 25 mm/sec 170A/φ ACCUCHART® Gould, Inc.



8-93

Position

Command



0.5 Hz \pm 0.1"

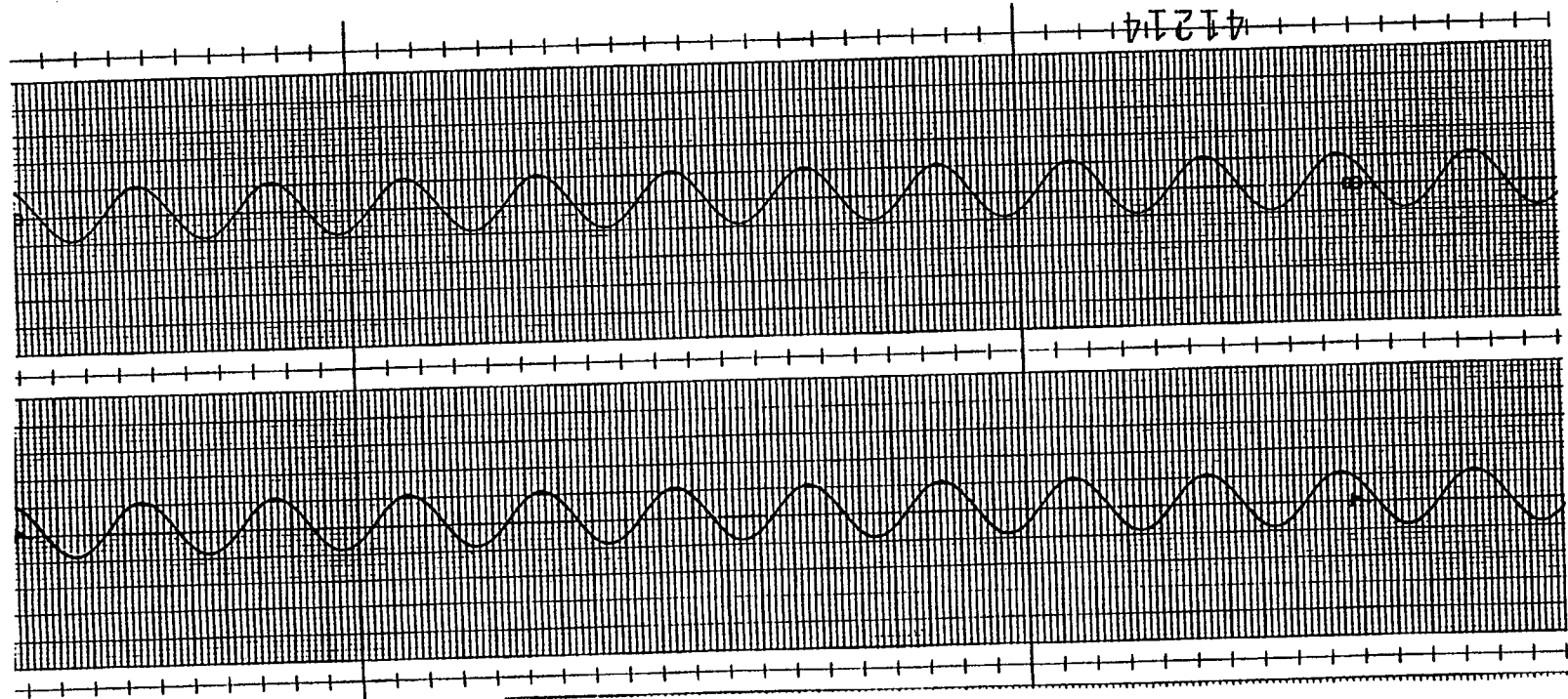
60 A/ ϕ

10.00 mm/sec

Cleveland, Ohio

Printed in U.S.A. ...

41216



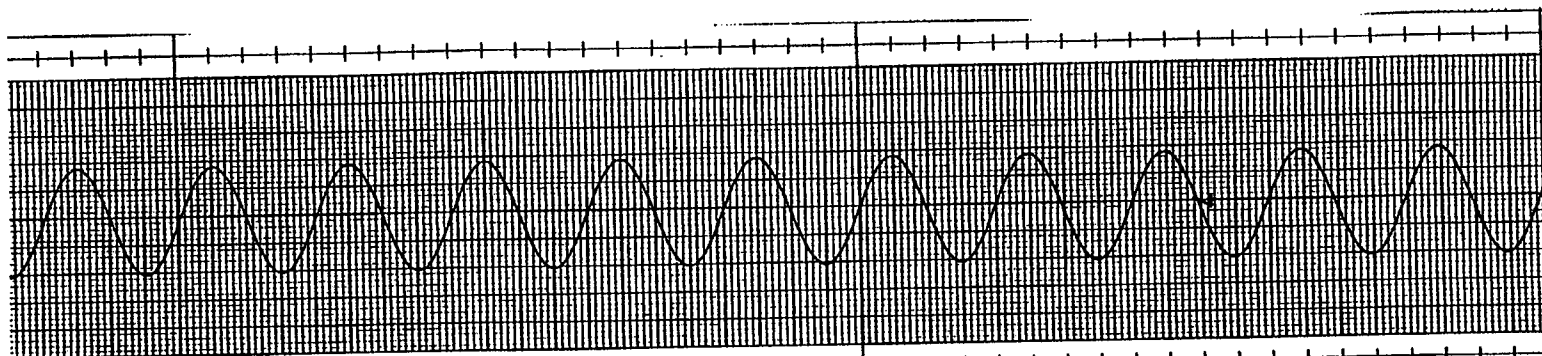
position

plasma

0.5 Hz \pm 0.25" 60H/φ 10.0 mm/sec

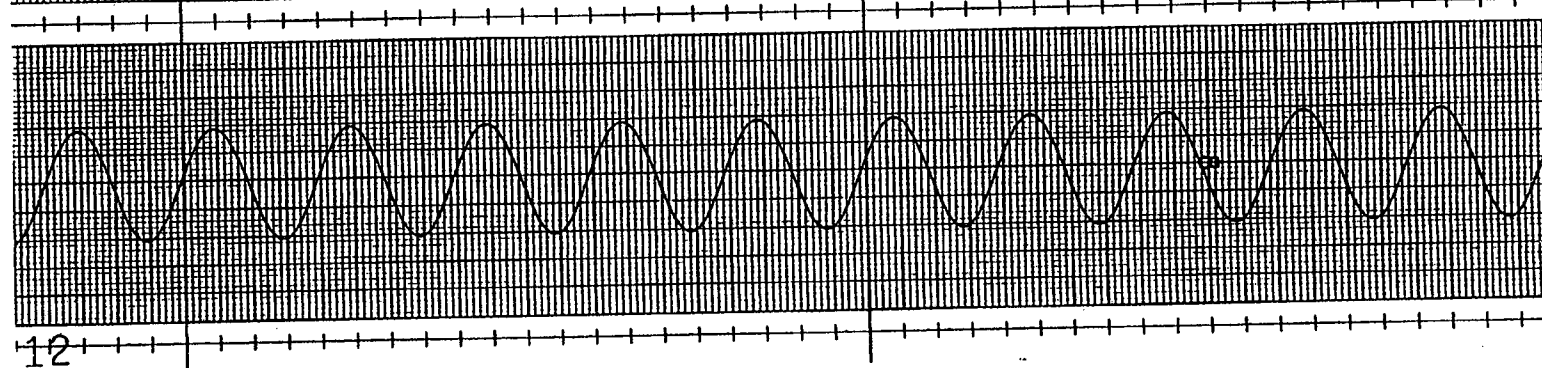
8-12-73

position



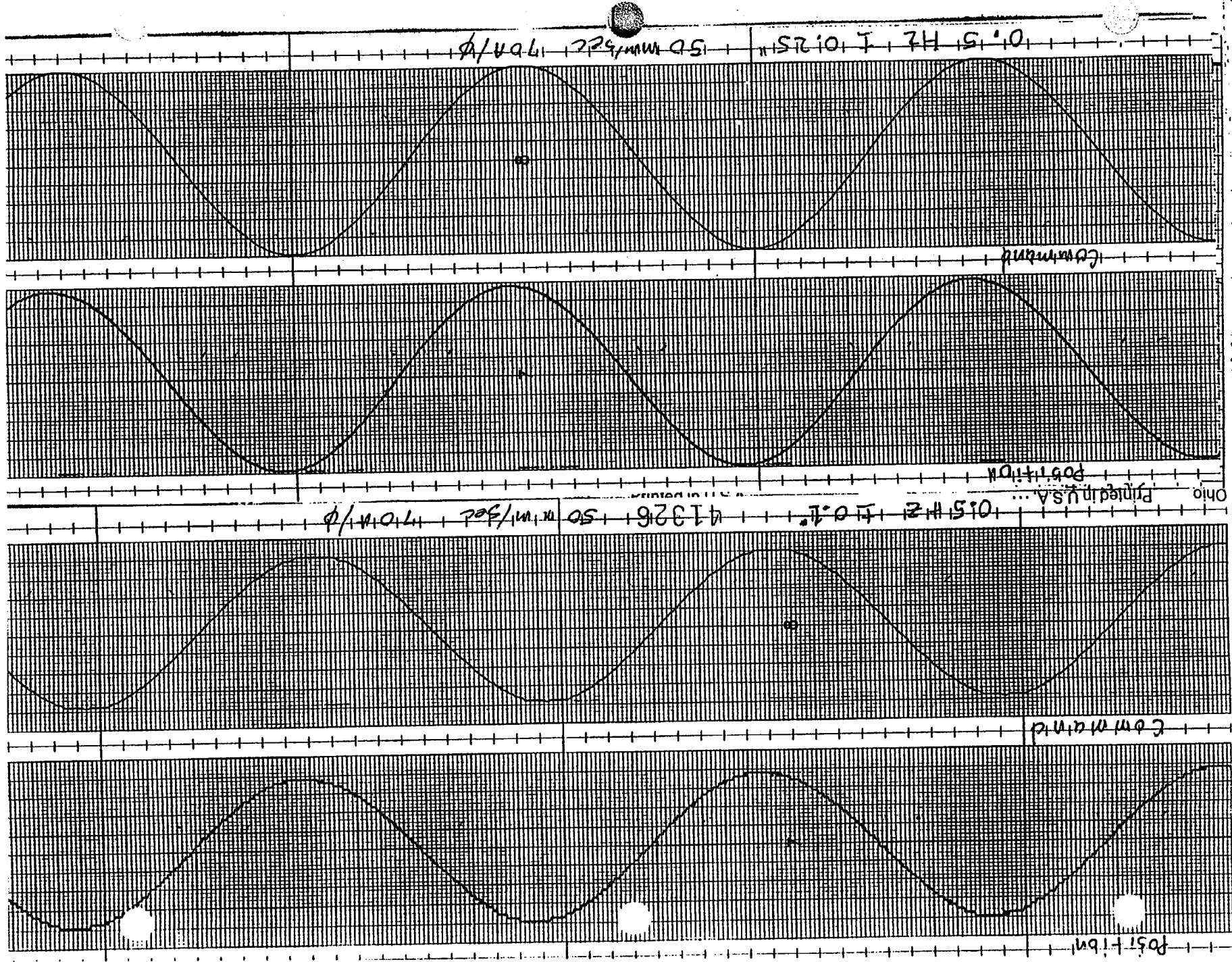
135

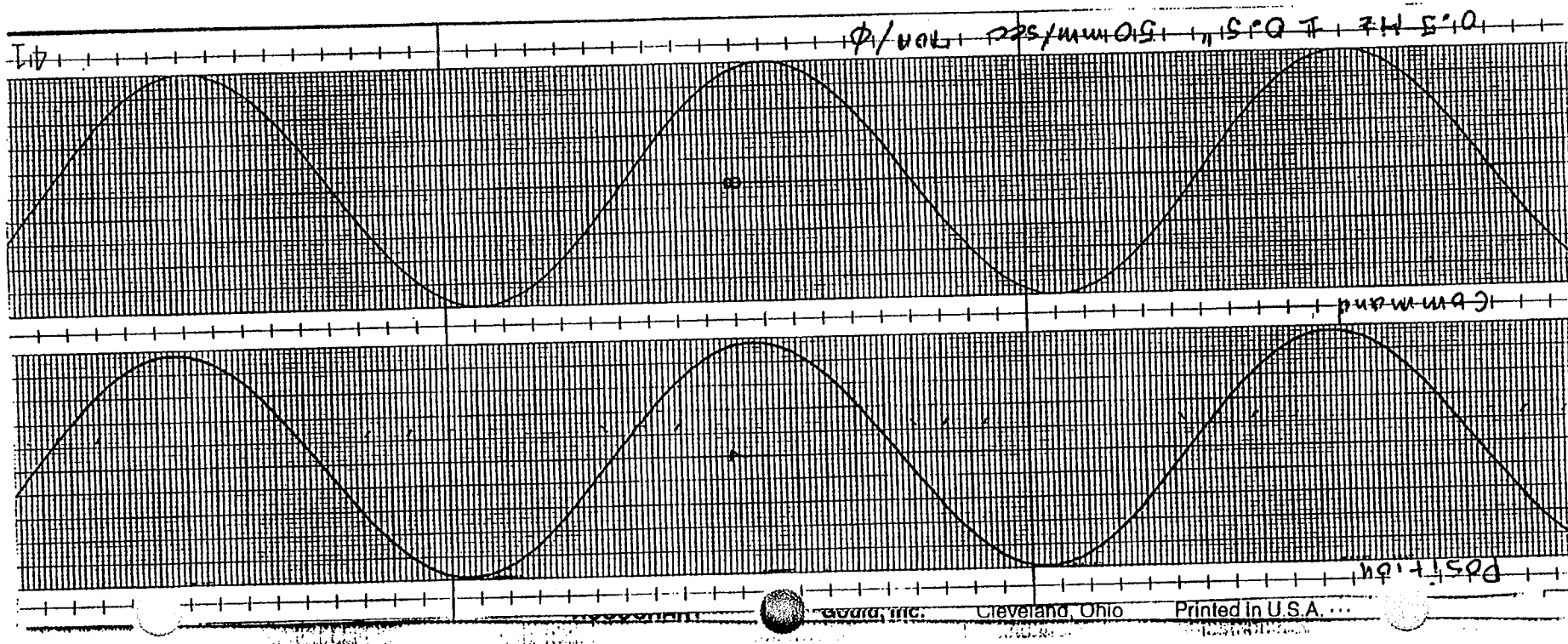
command



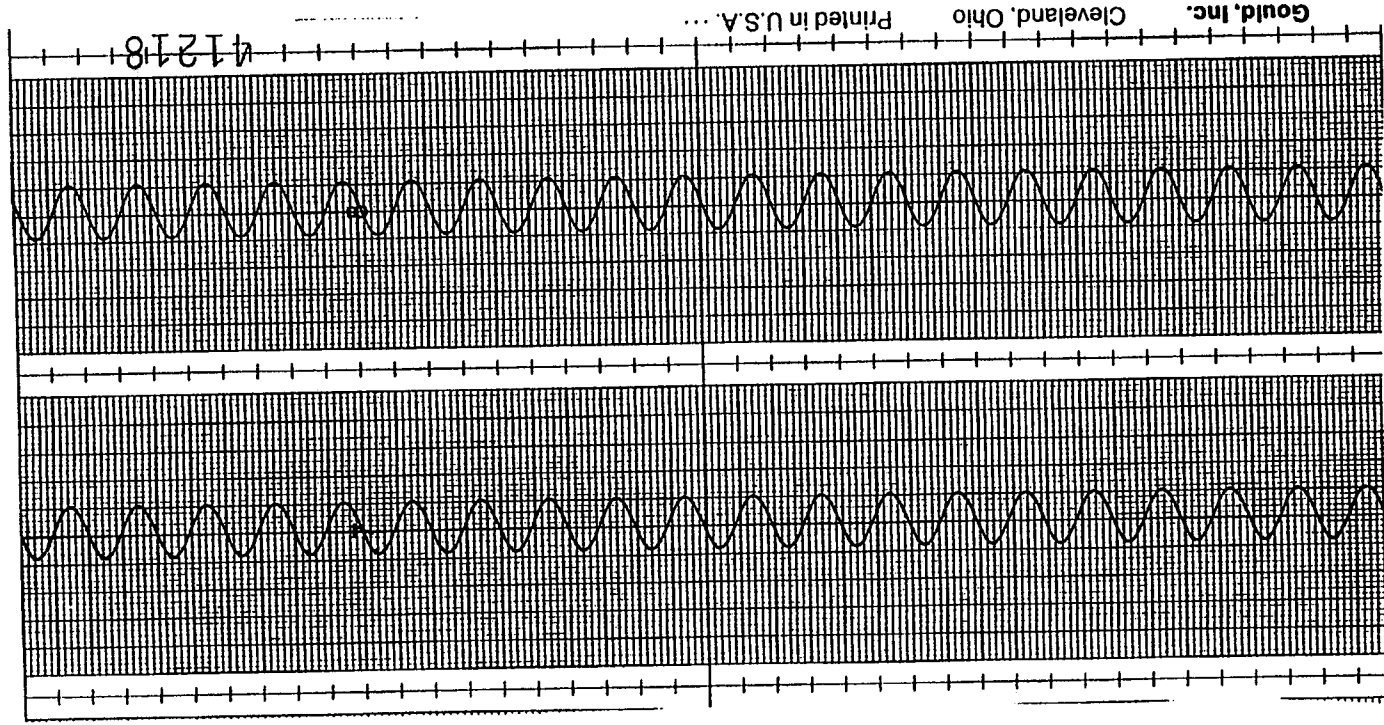
12

$0.5 \text{ Hz} \pm 0.5''$ $60 \text{ m}/\phi$ $10.0 \text{ min}/\text{sec}$





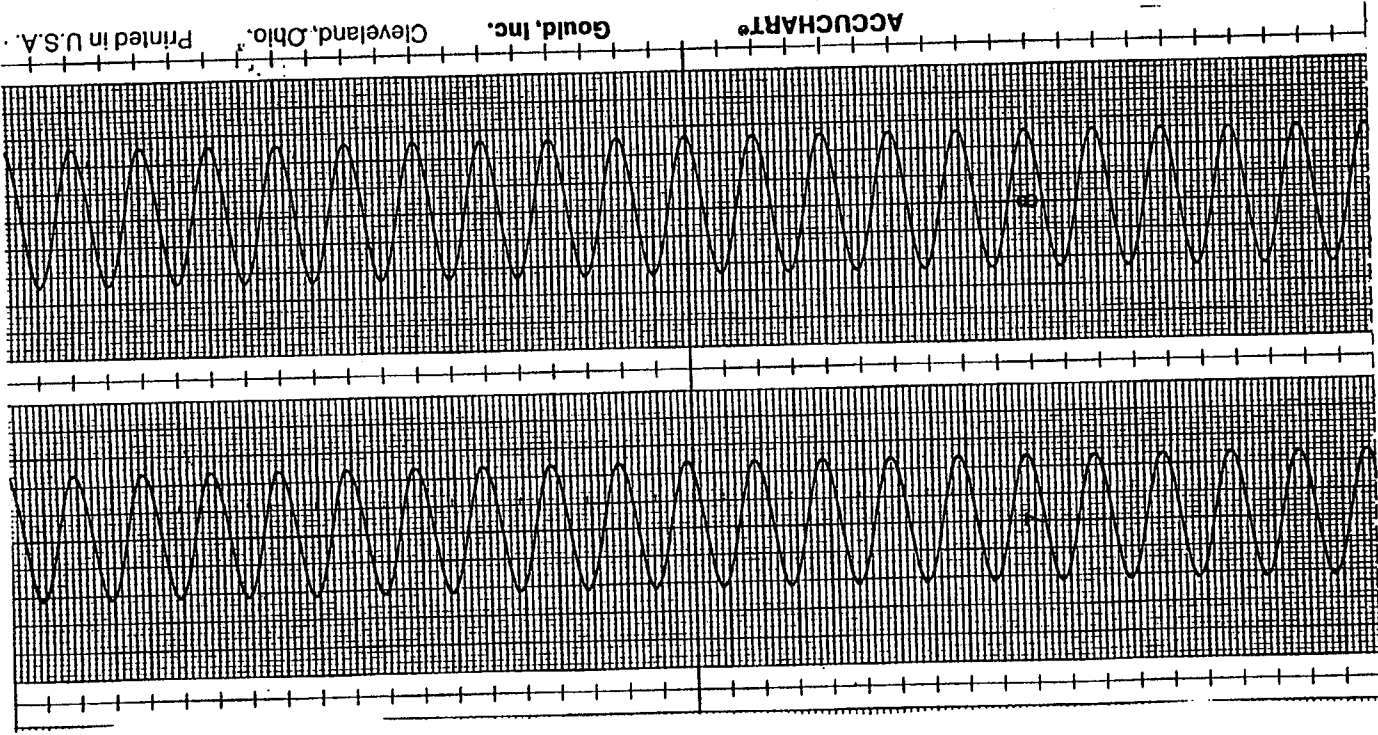
8-12-93



1.0 Hz \pm 0.1" 60V/φ 10.0 mm/sec

Gould, Inc. Cleveland, Ohio Printed in U.S.A. ...

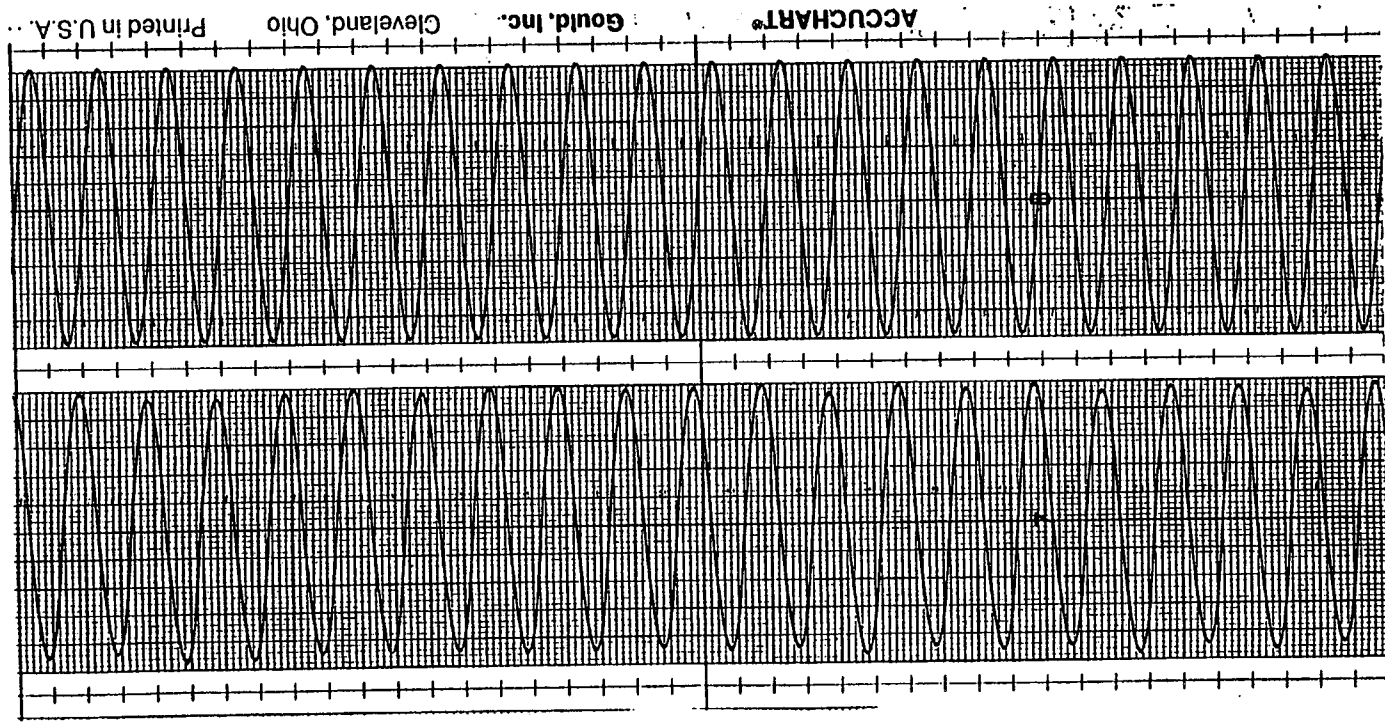
41218



Command

Position

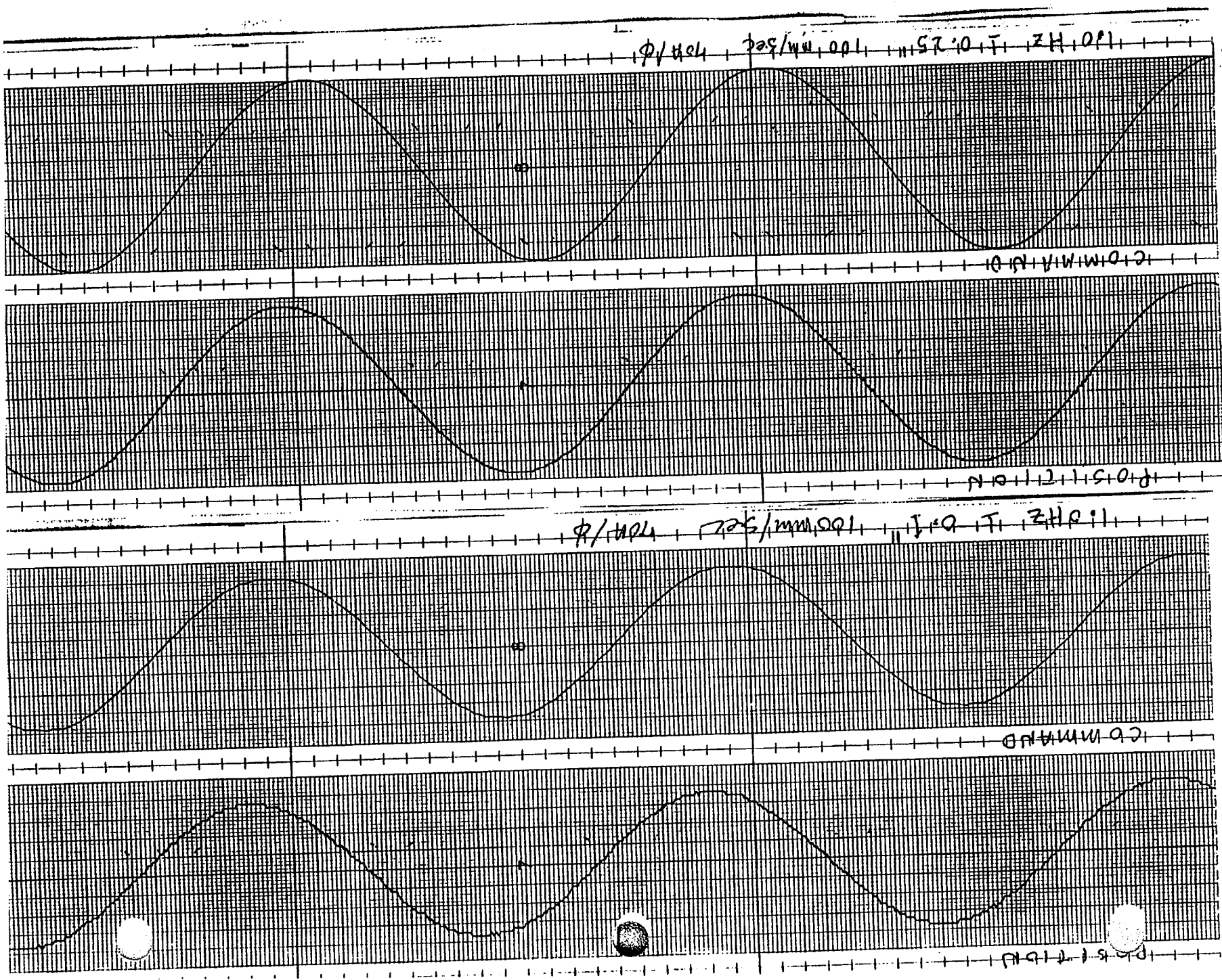
1.0 Hz ± 0.25 " 60H/ ϕ 10.0 mm/sec

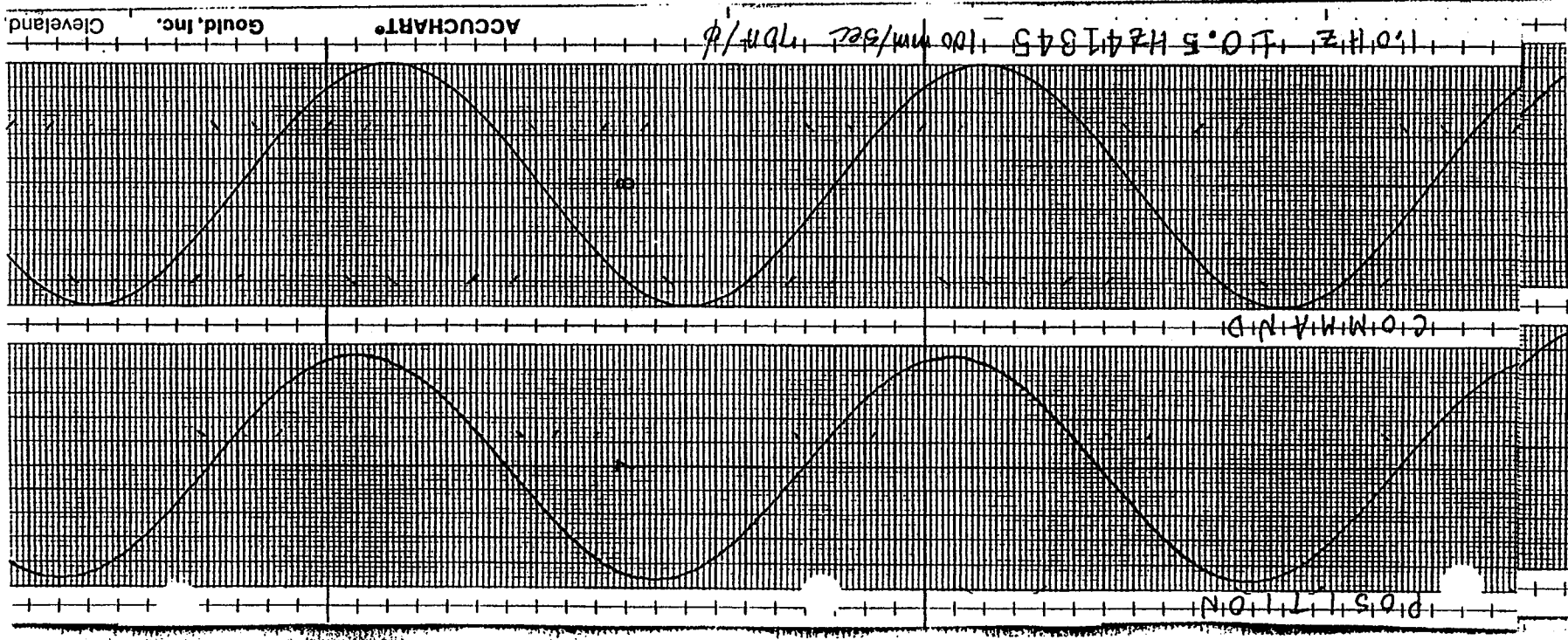


1.0 Hz ± 0.5 " 60H/ ϕ 10mm/sec

Command

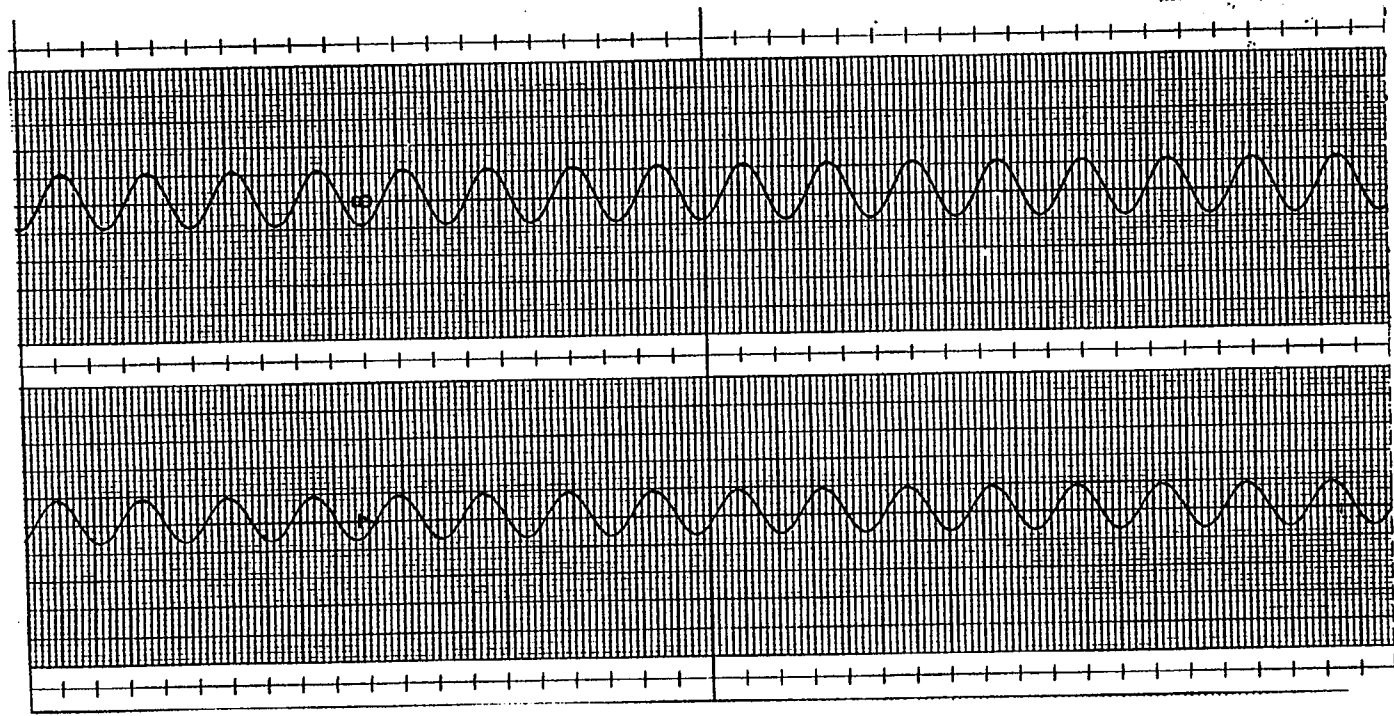
Position





AccuCHART[®] Gould, Inc. Cleveland

62-71-Q



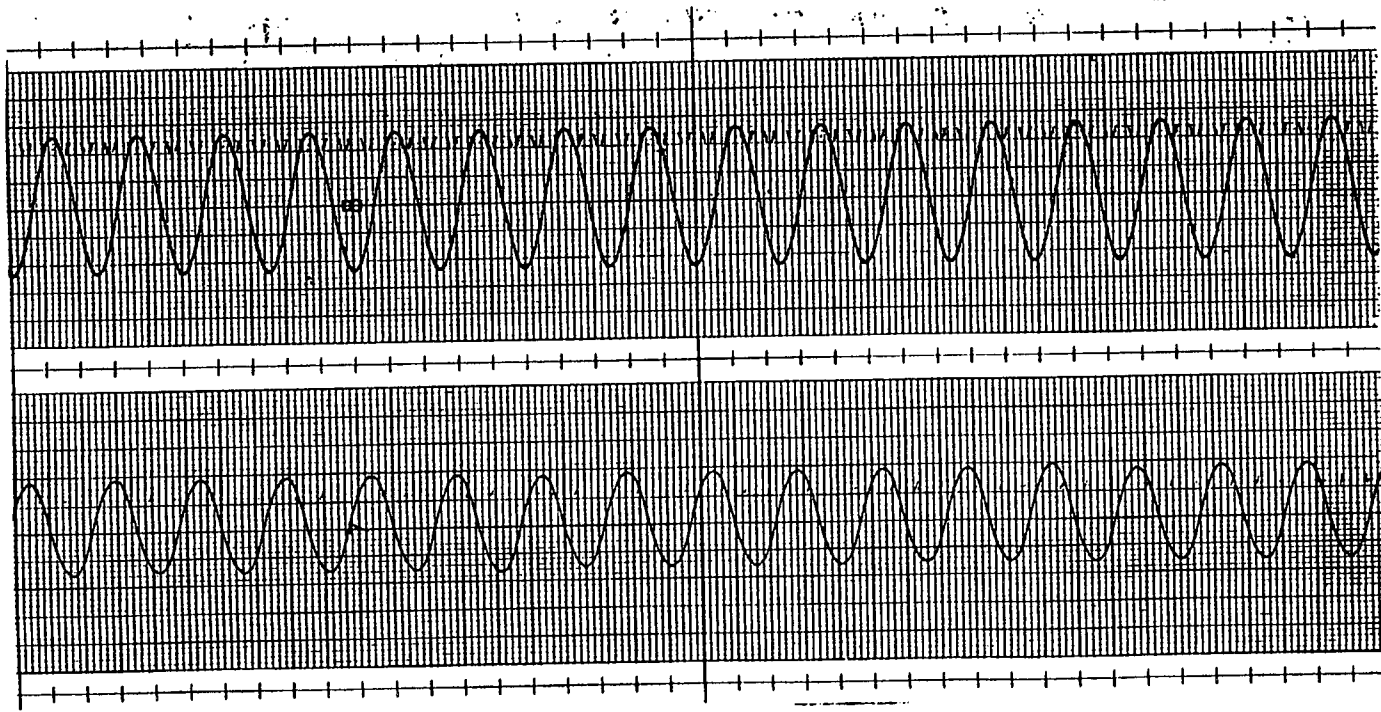
2.0 Hz \pm 0.1" ϕ /100. 20mm/sec

Command

Position

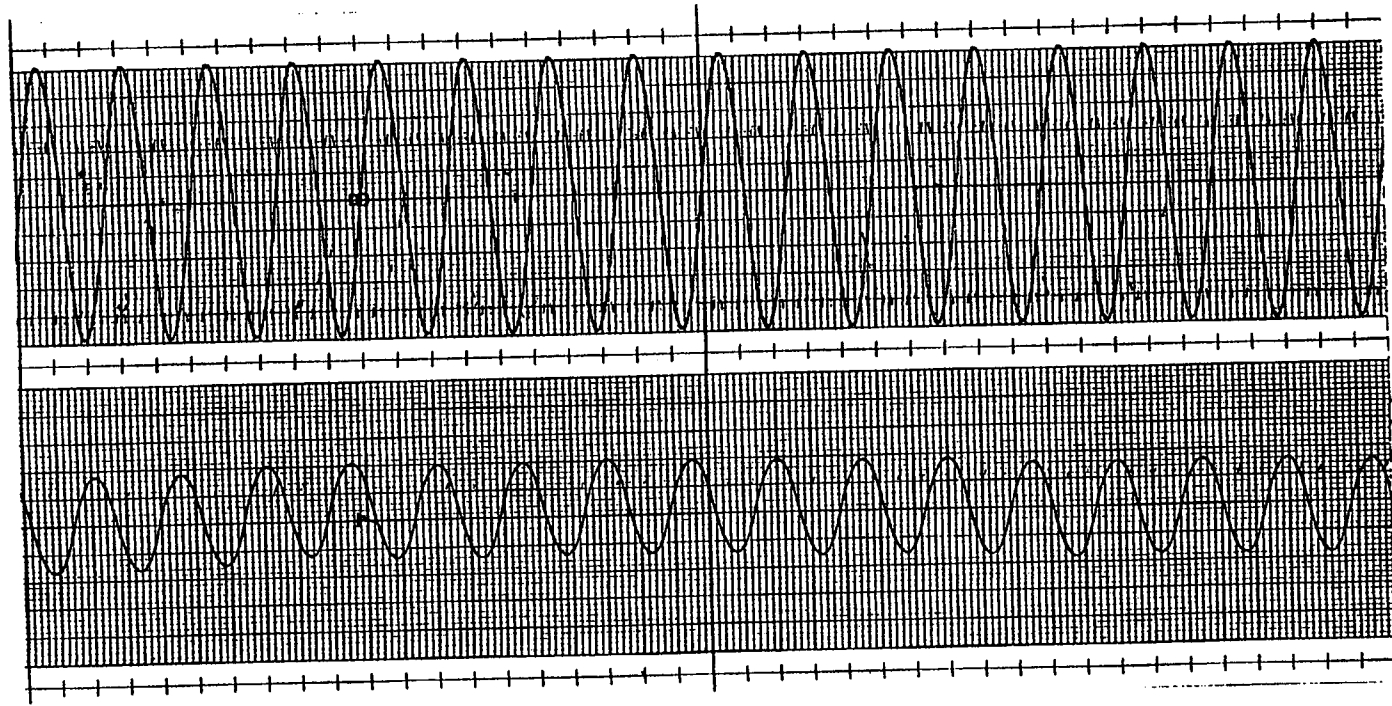
Command

Position



2.0 Hz \pm 0.25" 700/φ 25mm/sec

12-93



2.0 Hz ± 0.5 " 100 ϕ 25 mm/sec

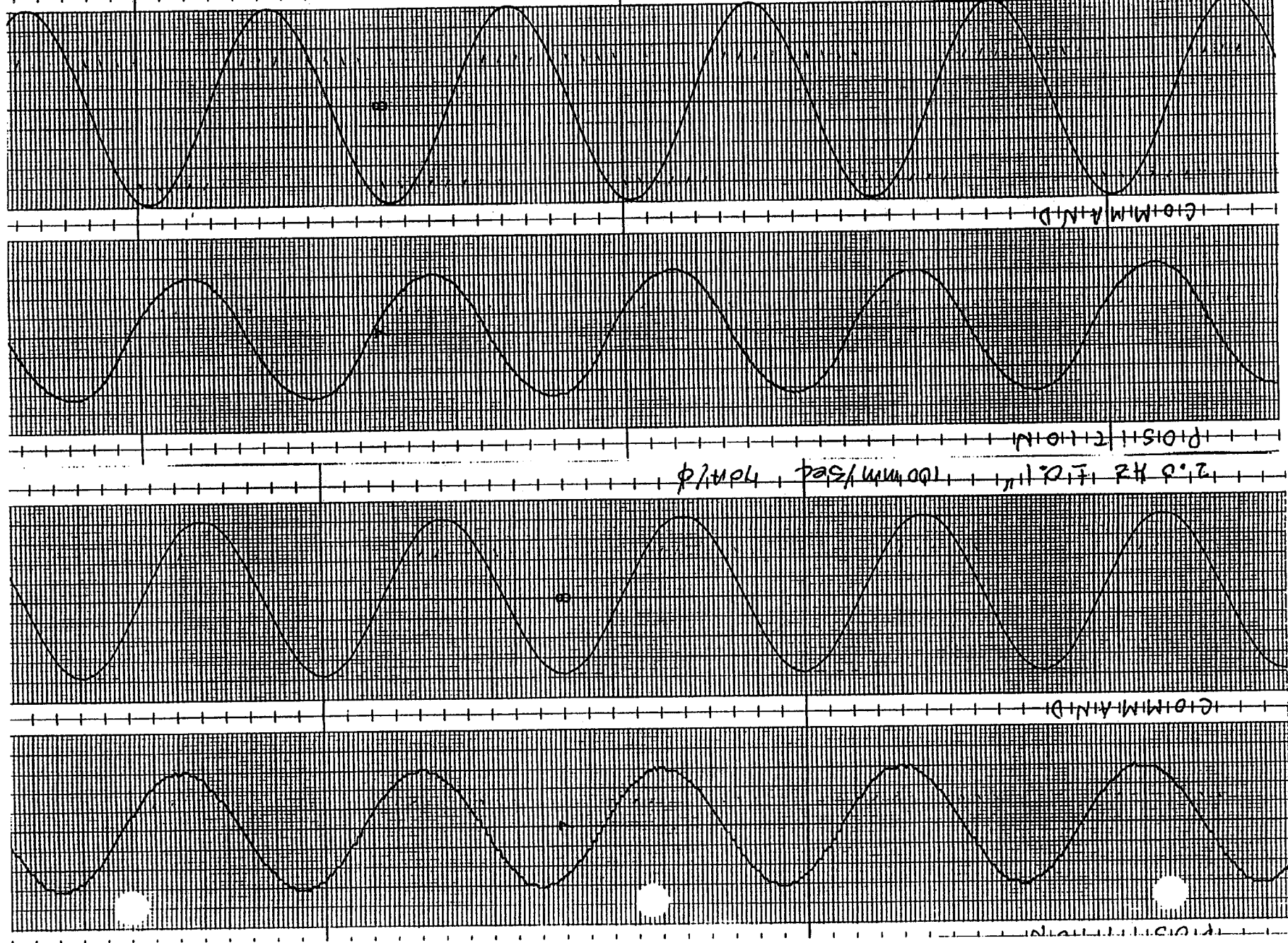
Position

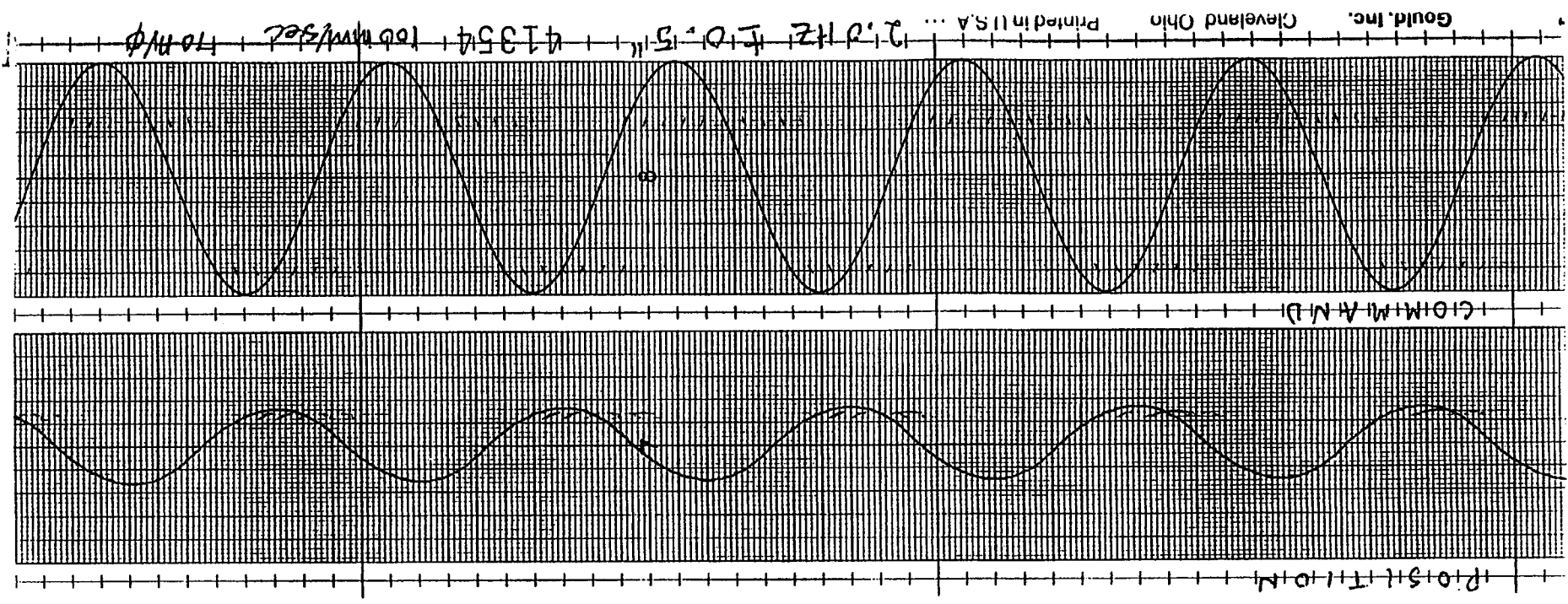
Command

Gould, Inc.

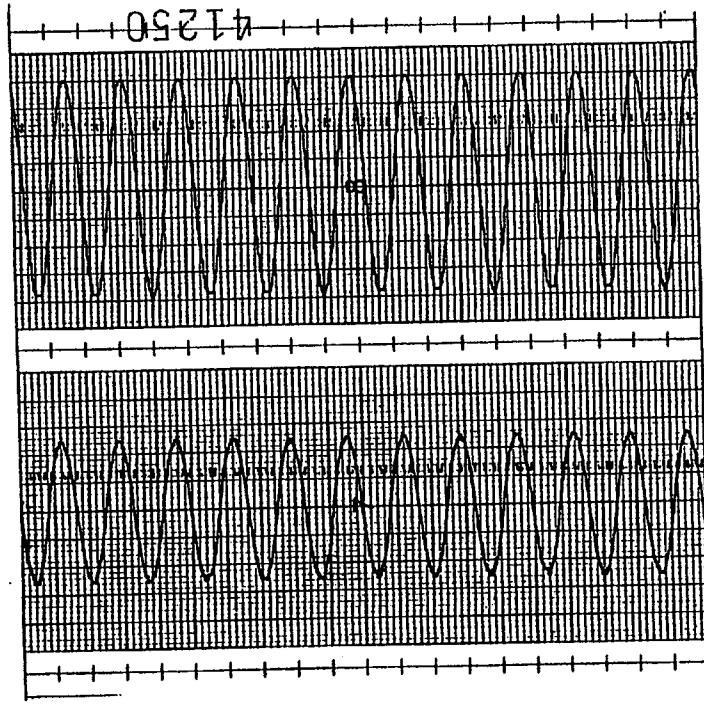
ACCU-CHART

2.5 Hz 100 mm/sec 100 mm/div 100 mm/div 100 mm/div 100 mm/div





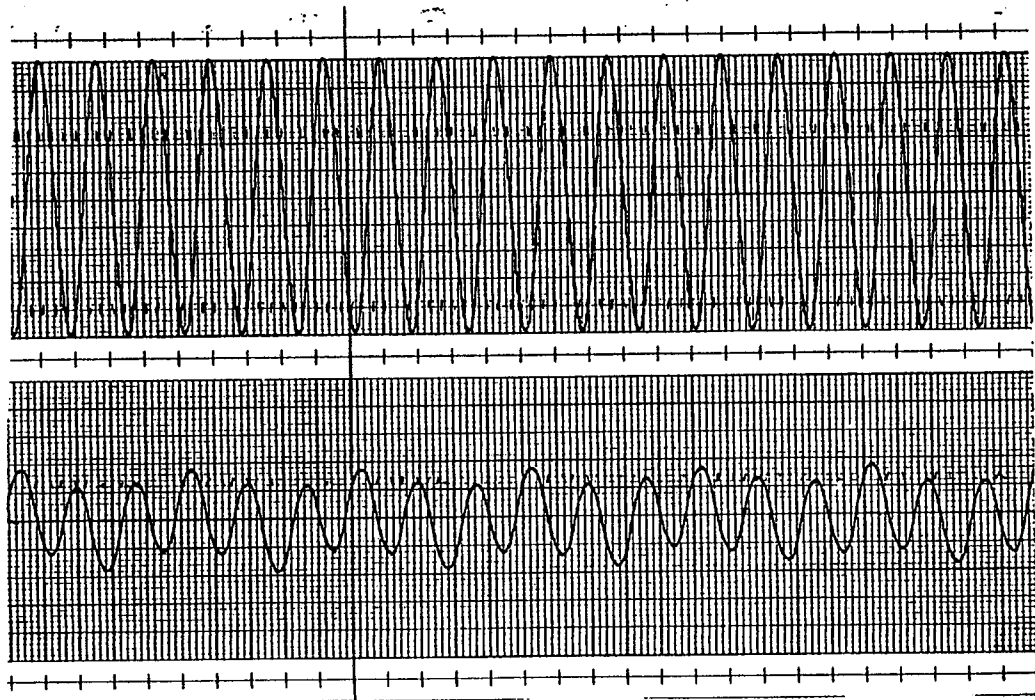
8-15-95



Position

Command

3.0 Hz
0.1 " 10A/φ
25 mm/sec



Position

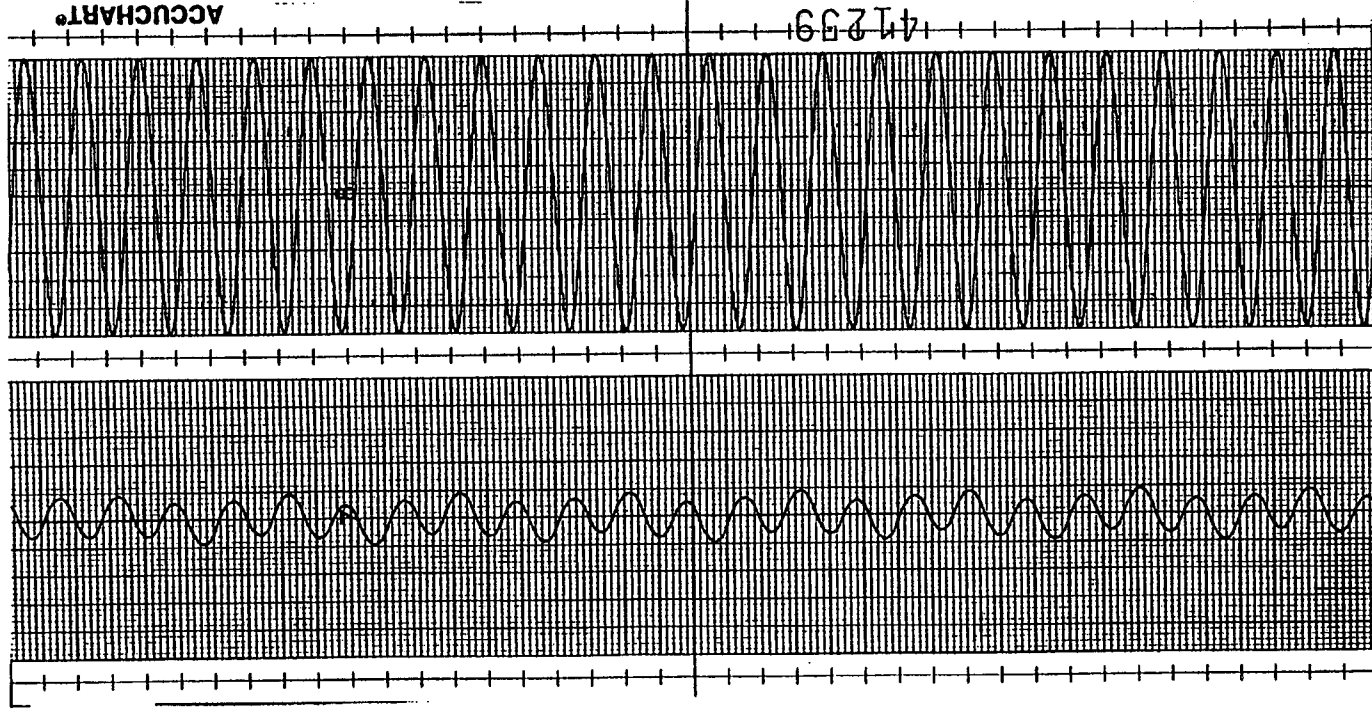
Command

3.0 HZ \pm 0.25" 70A/ ϕ 25 mm/s

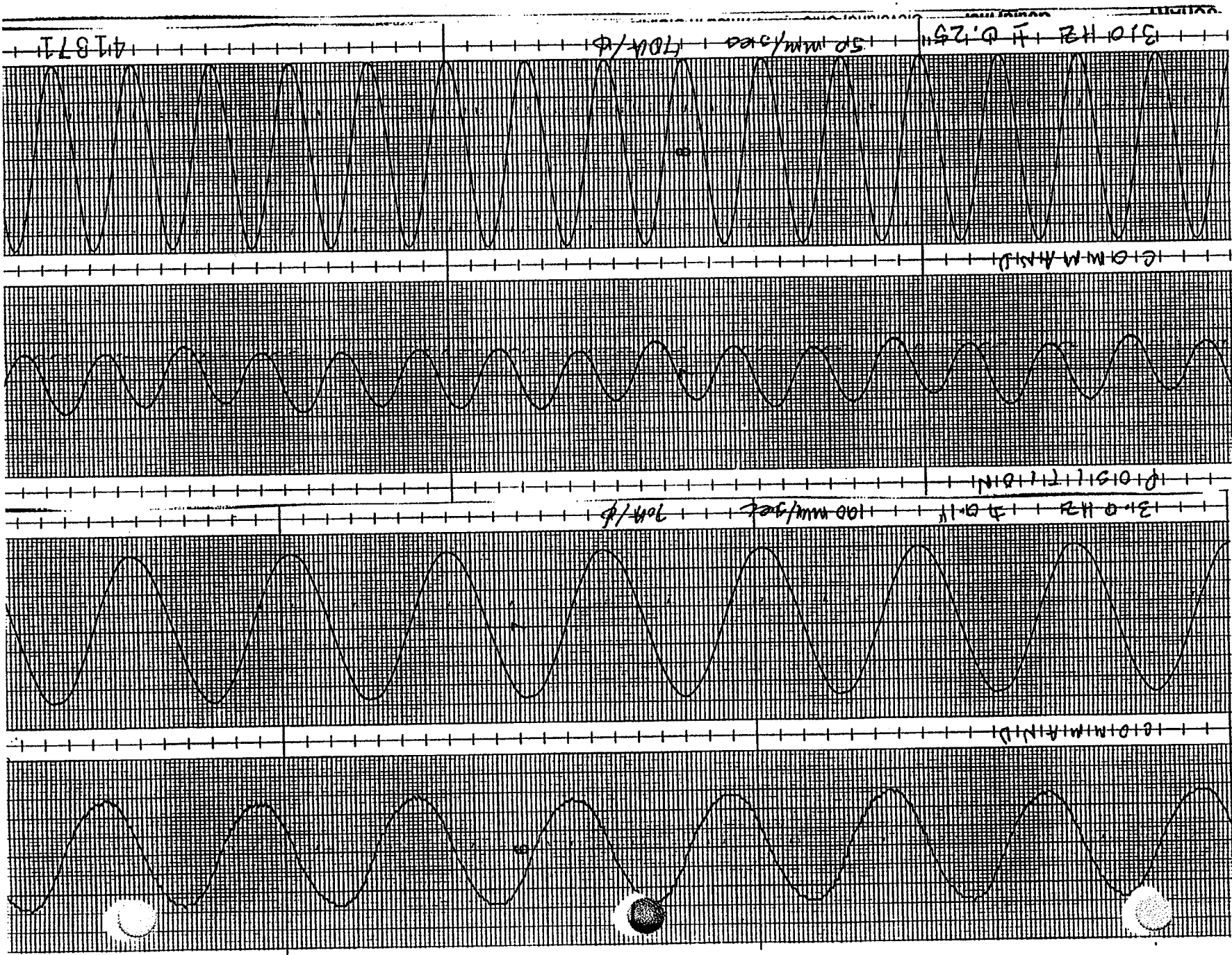
8-13-93

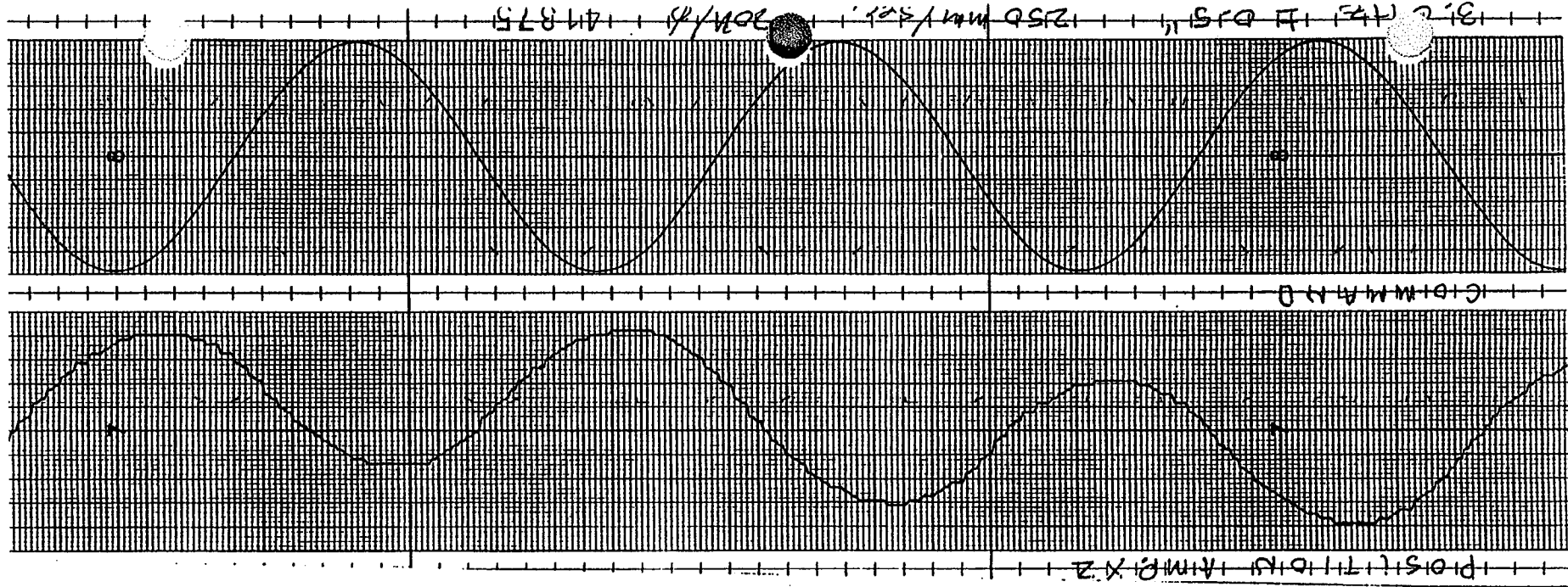
Command

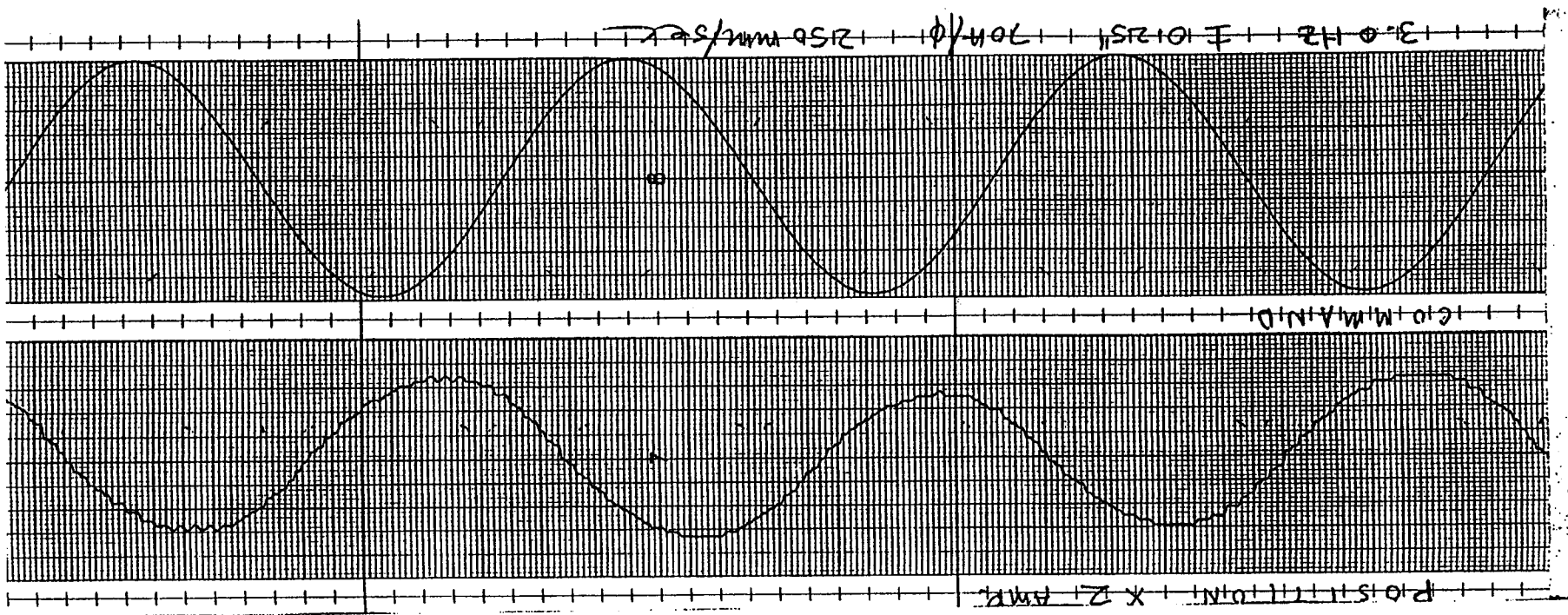
Position

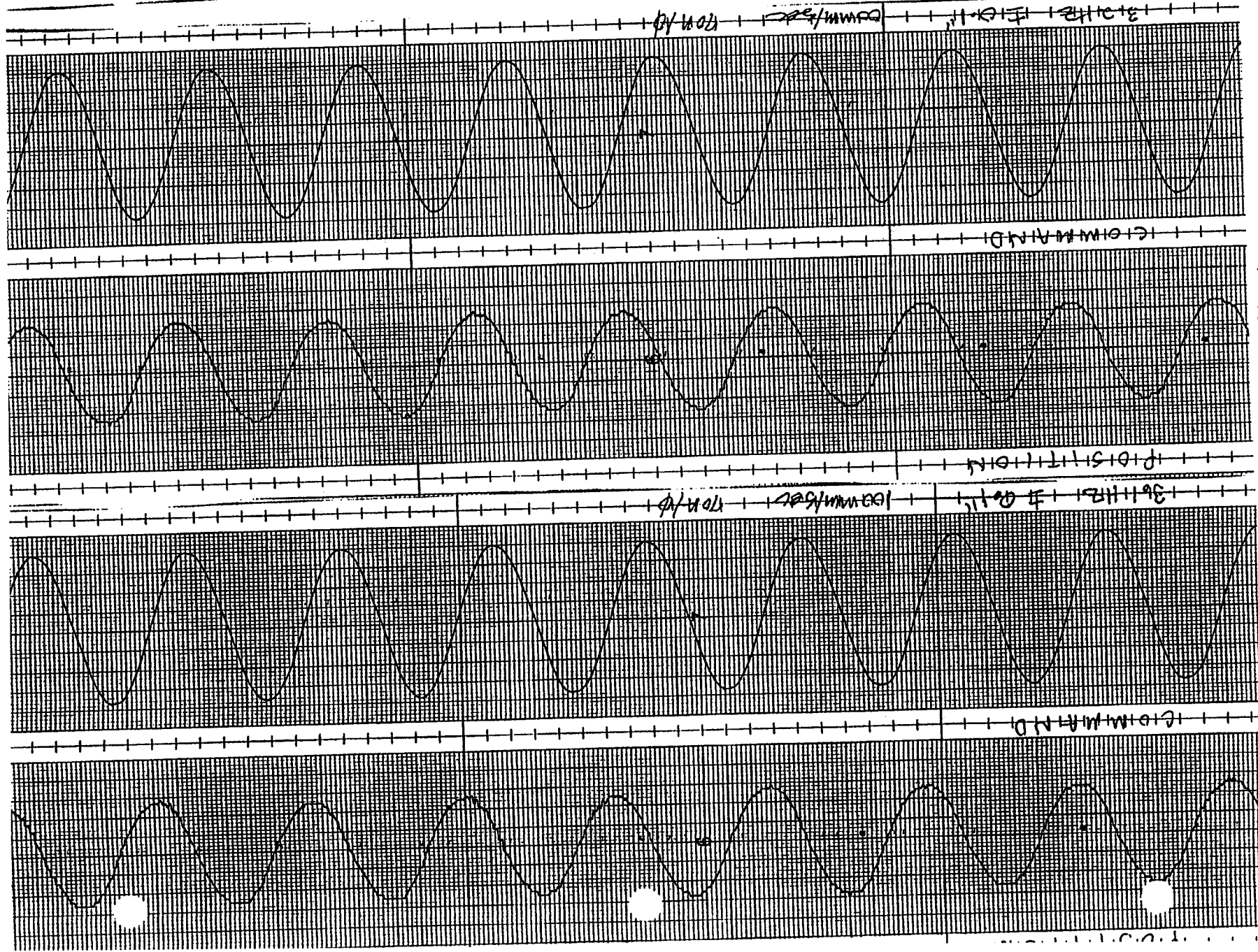


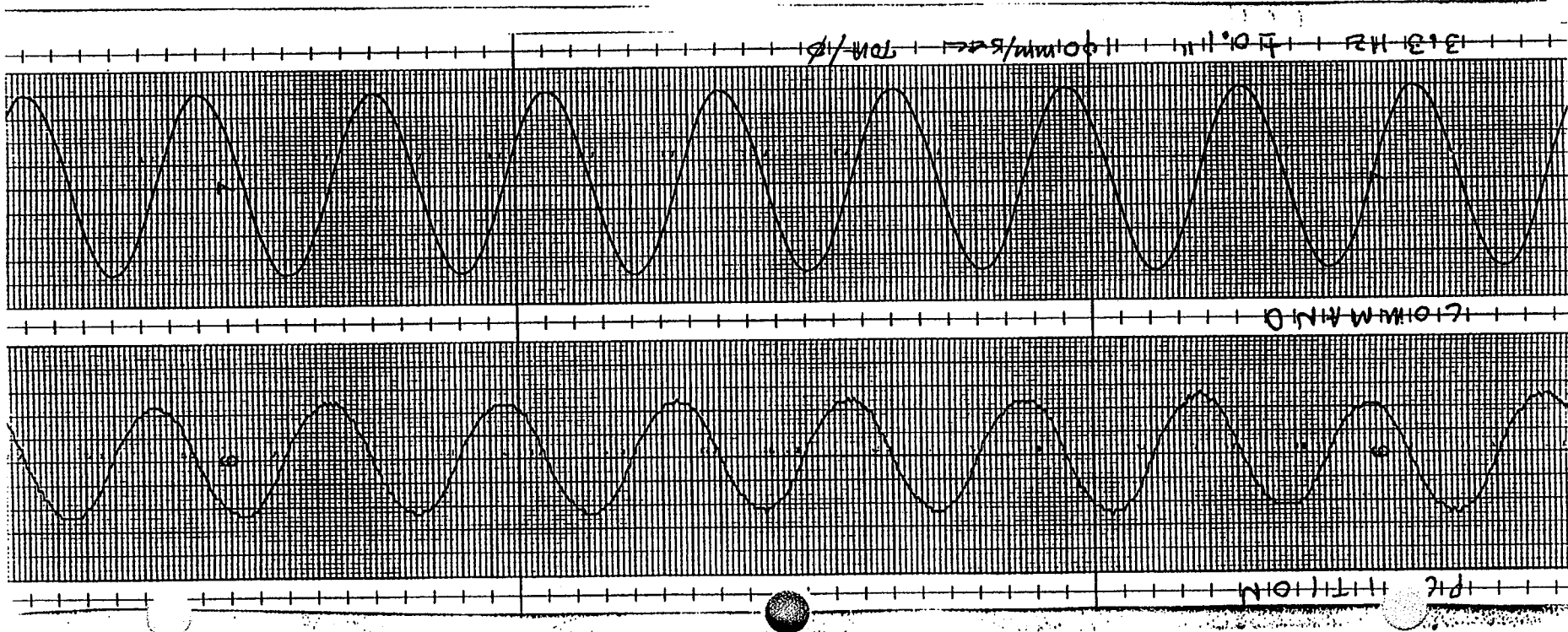
3.0 Hz ± 0.5 "
104/d
25 mm/sec

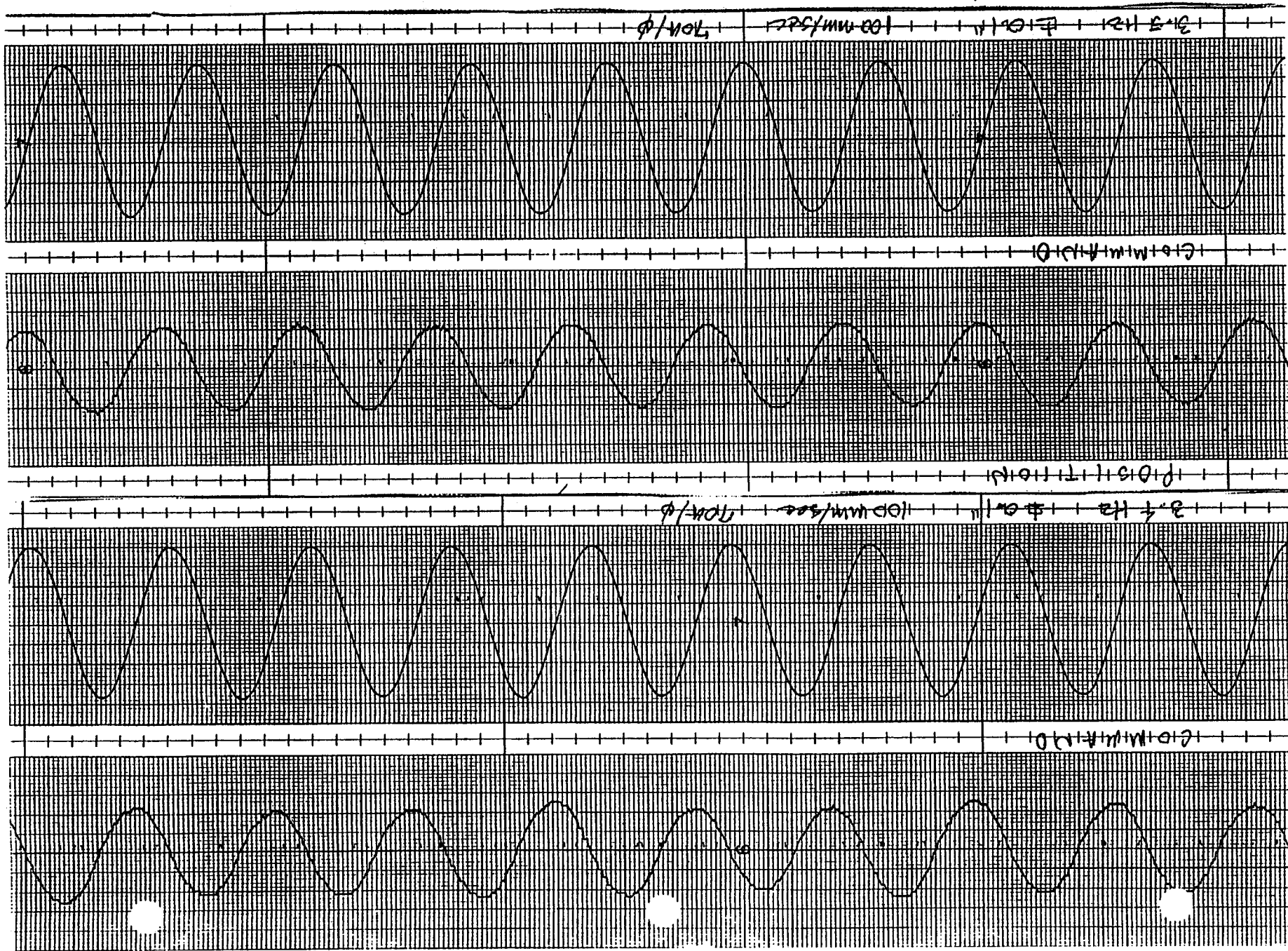


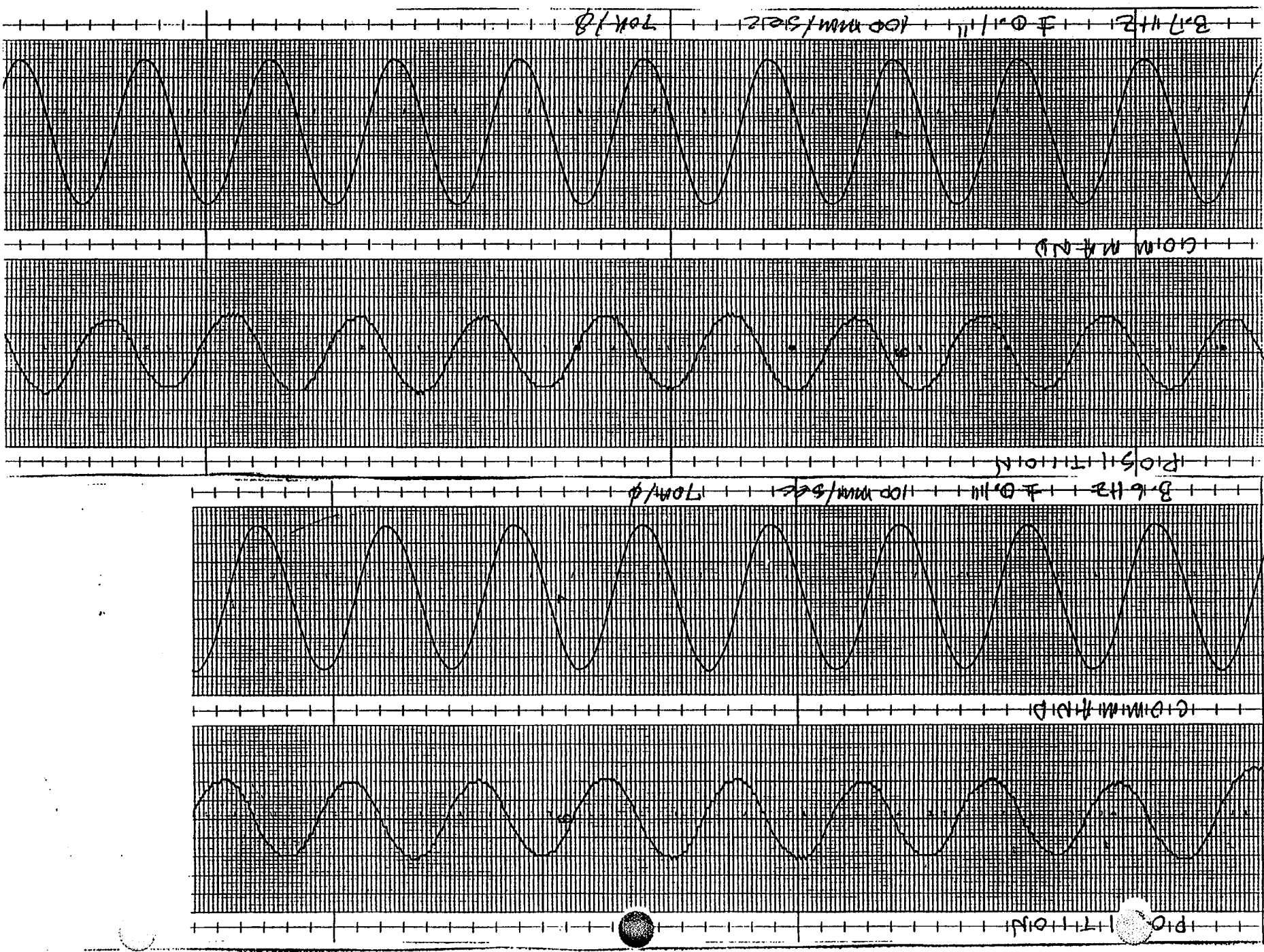


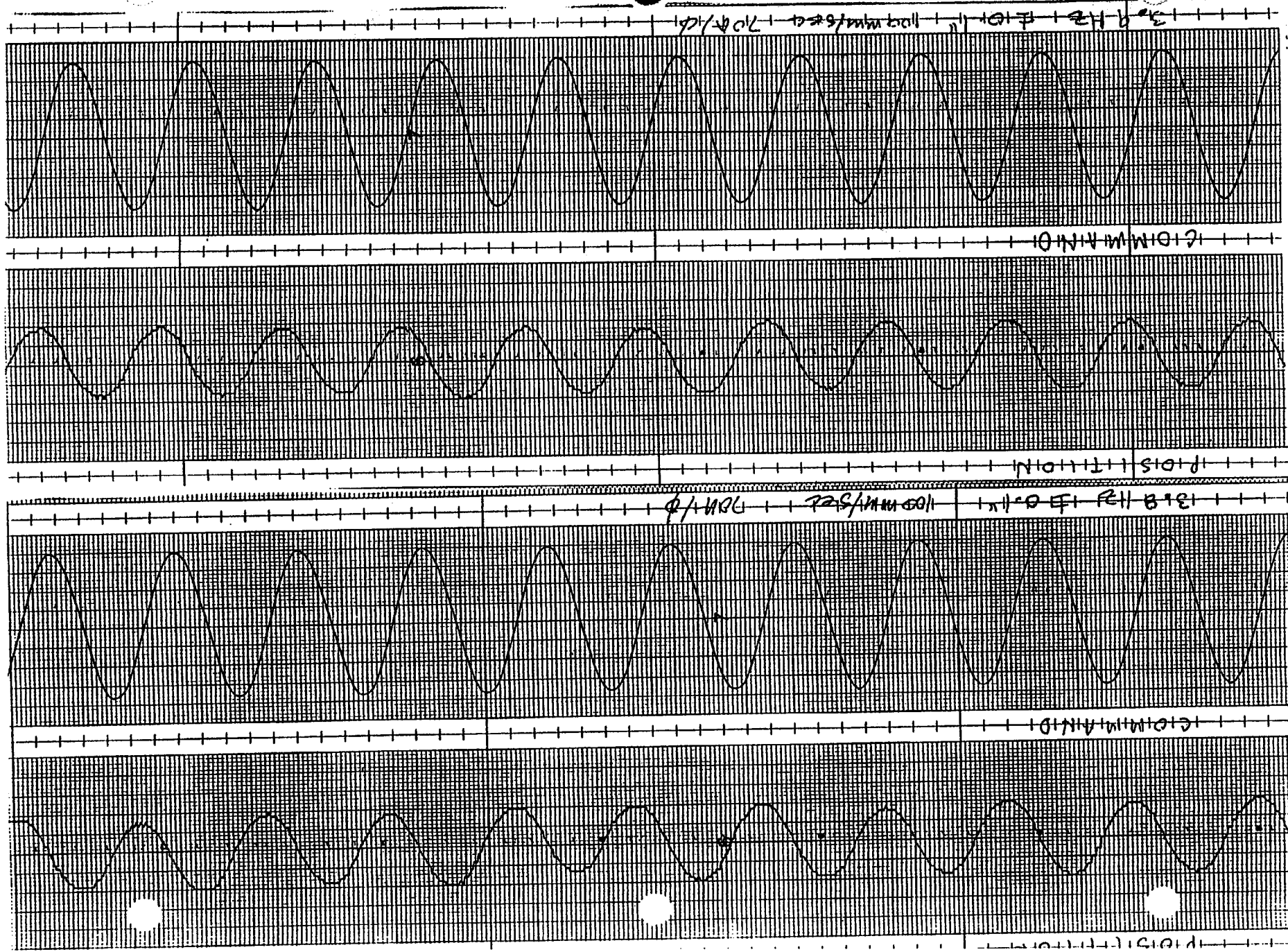






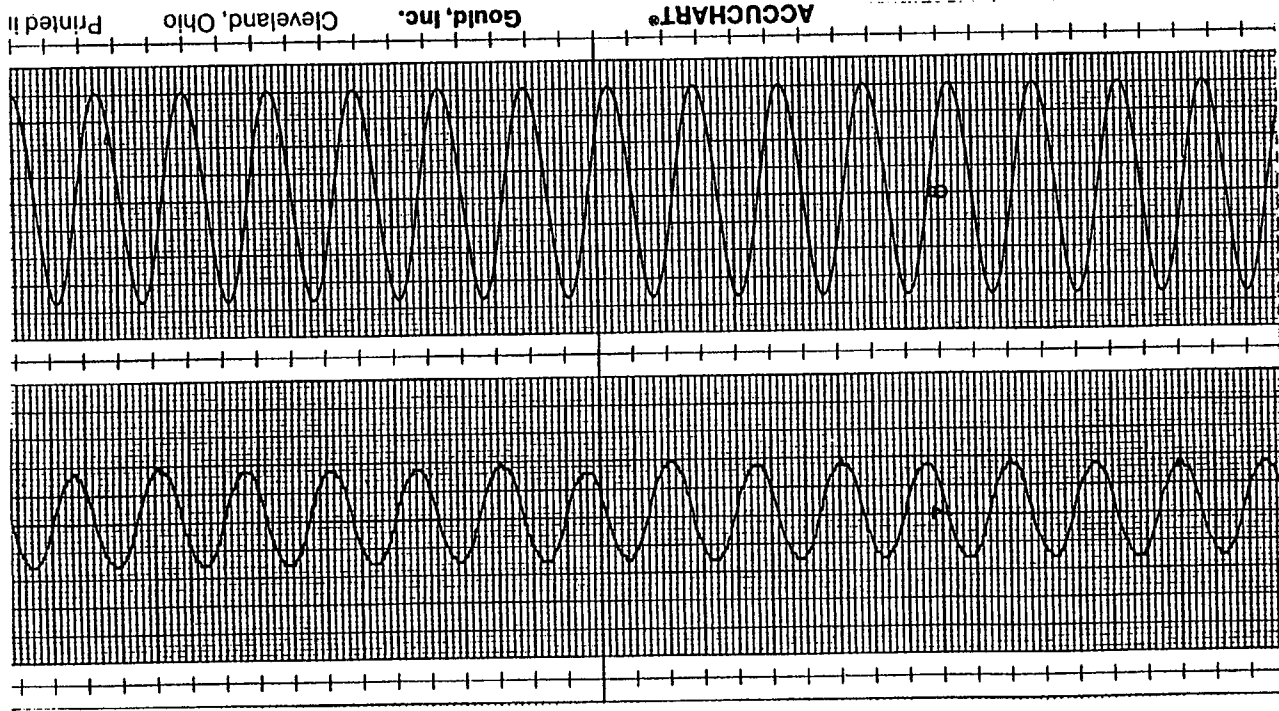






Command

Position



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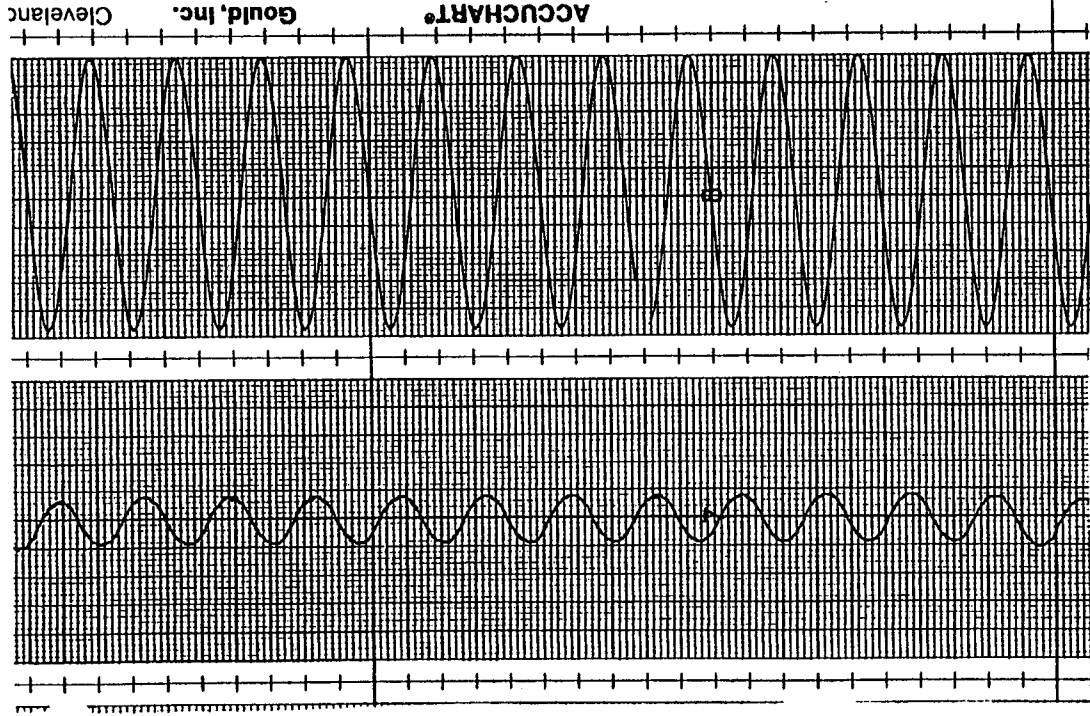
Cleveland, Ohio

Printed in

4.0 Hz \pm 0.1" 1000/phi 50 mm/sec

8-17-73

8-13-72

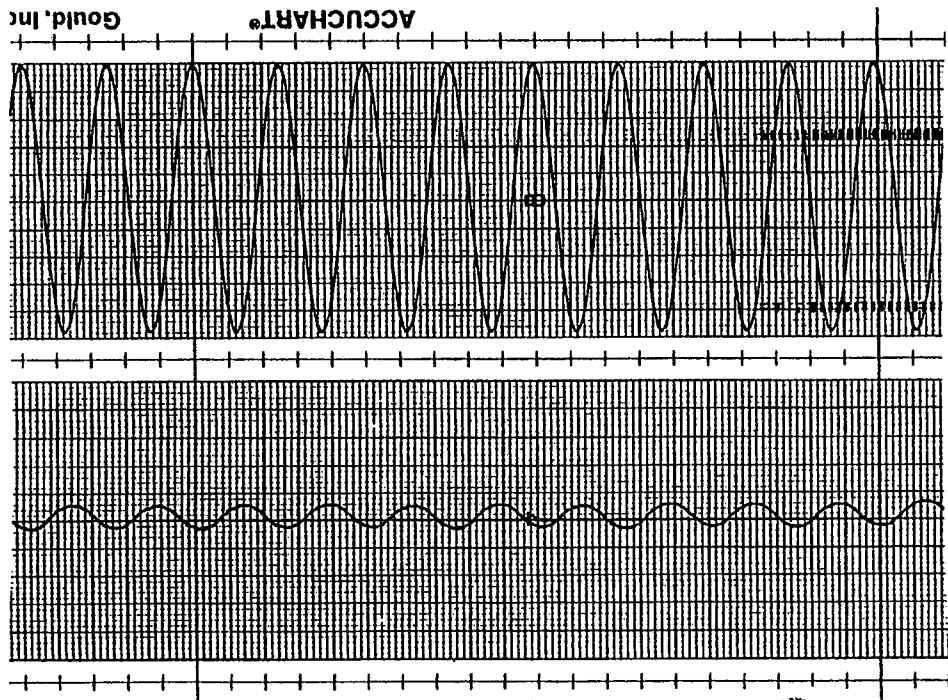


4.0 Hz ± 0.25 " $\phi/104$ 50 mm/sec

Position

Command

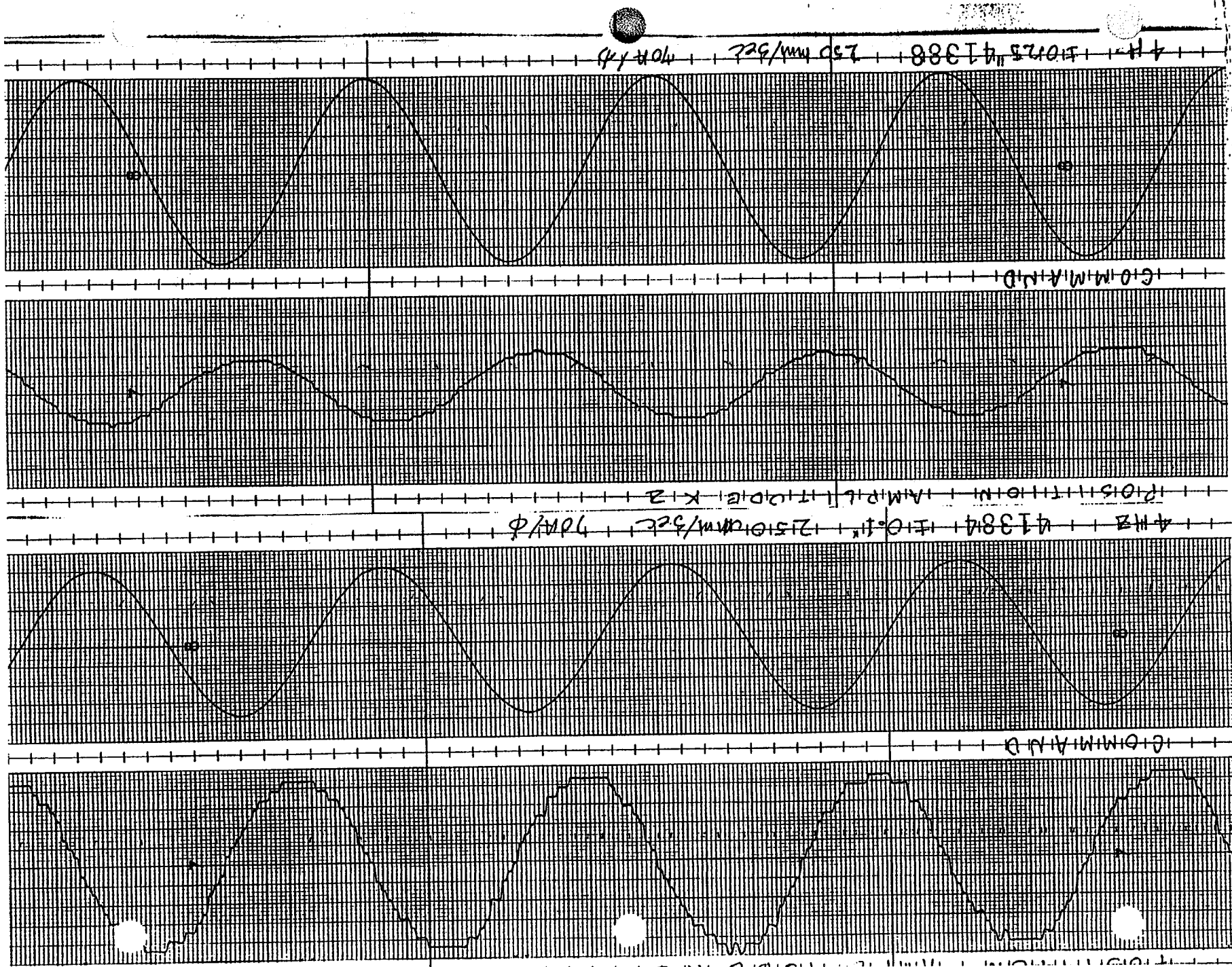
0-5-4

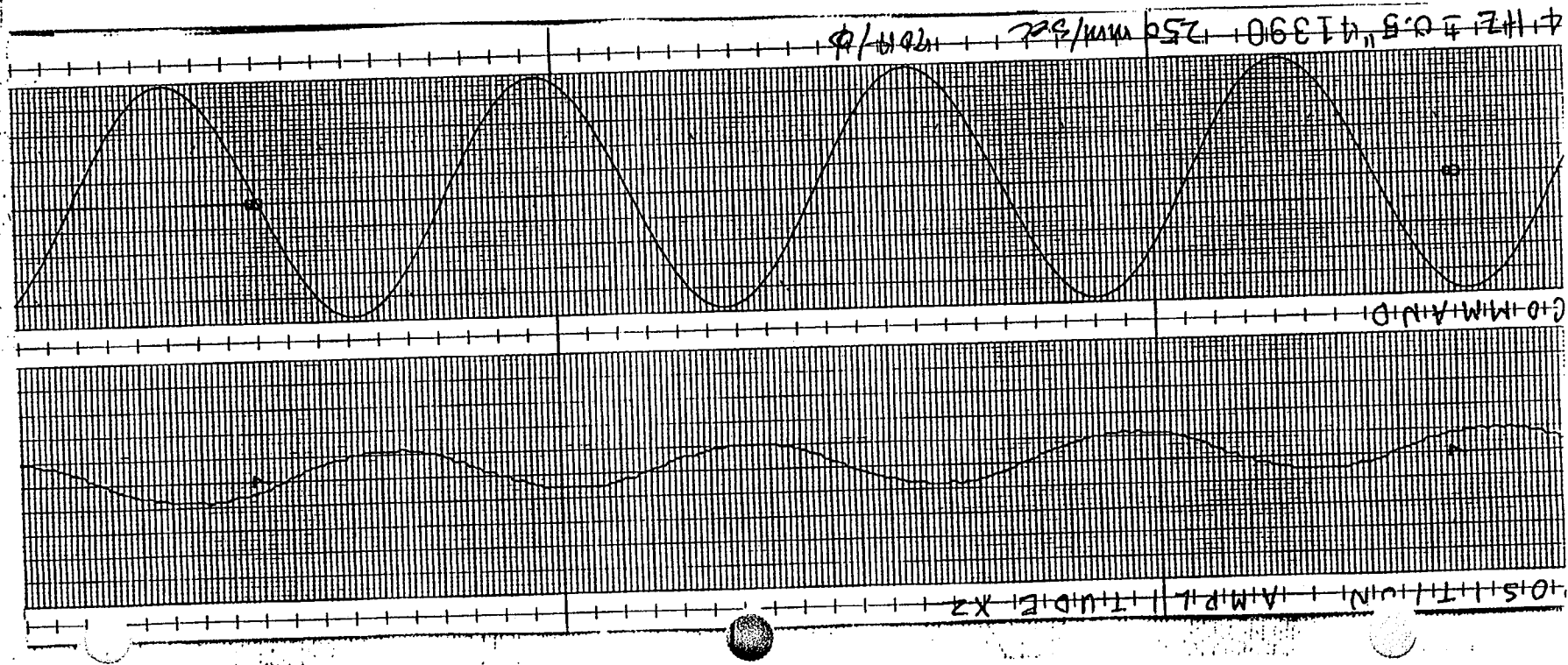


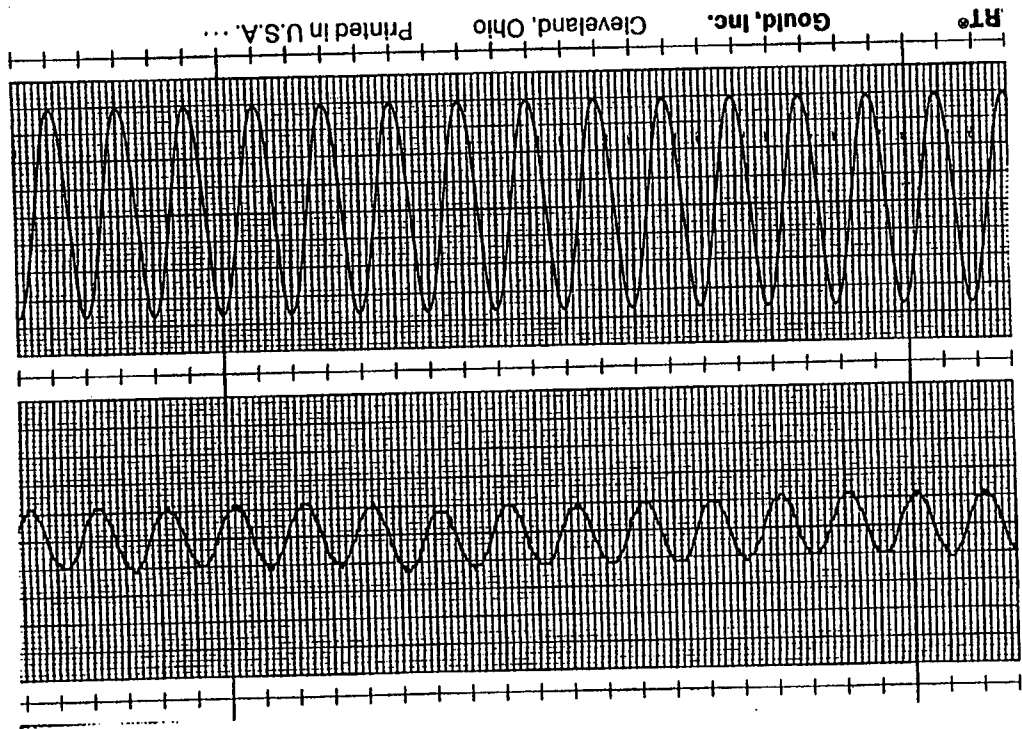
4.0 Hz ± 0.5 " 10V/ ϕ 50 mm/sec

Position

Command

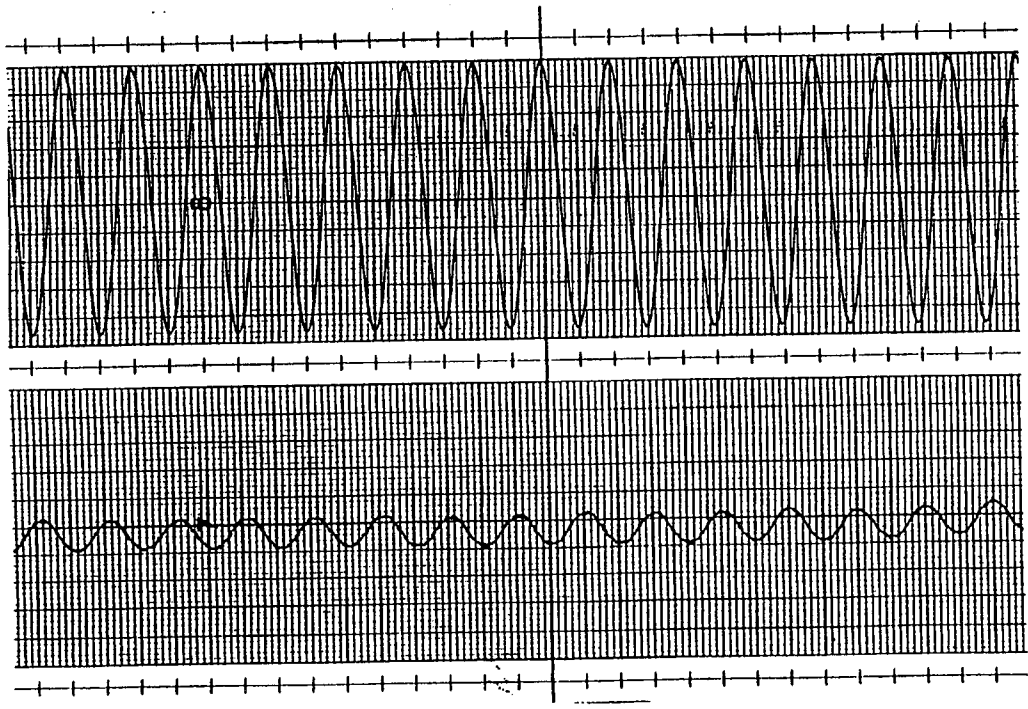






Position

Command

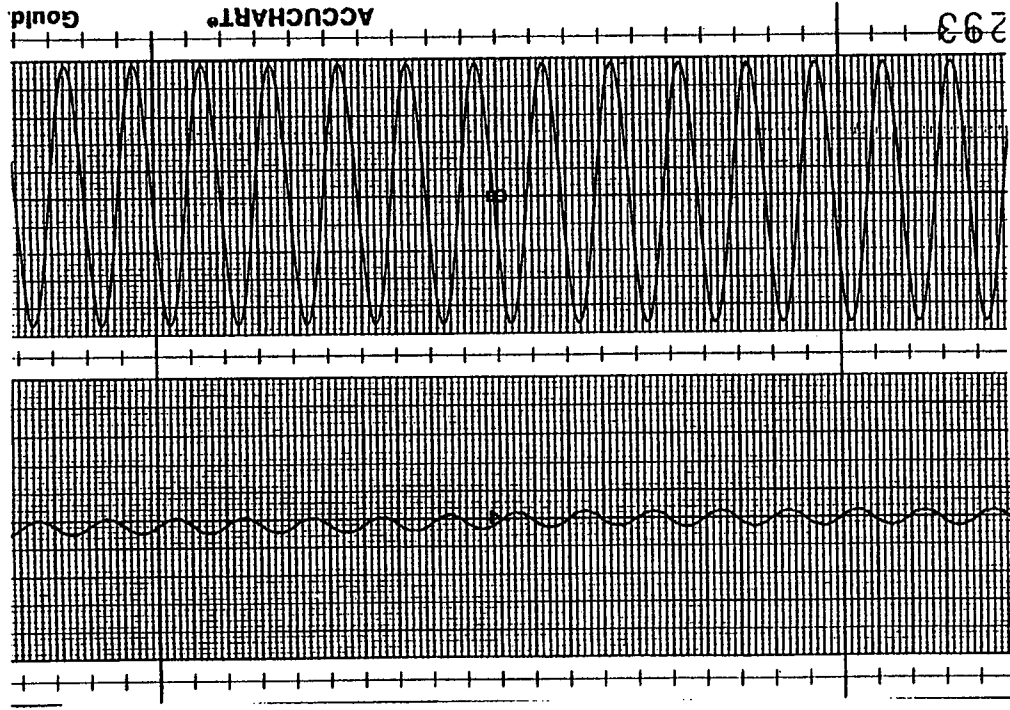


Command

Position

8-13-83

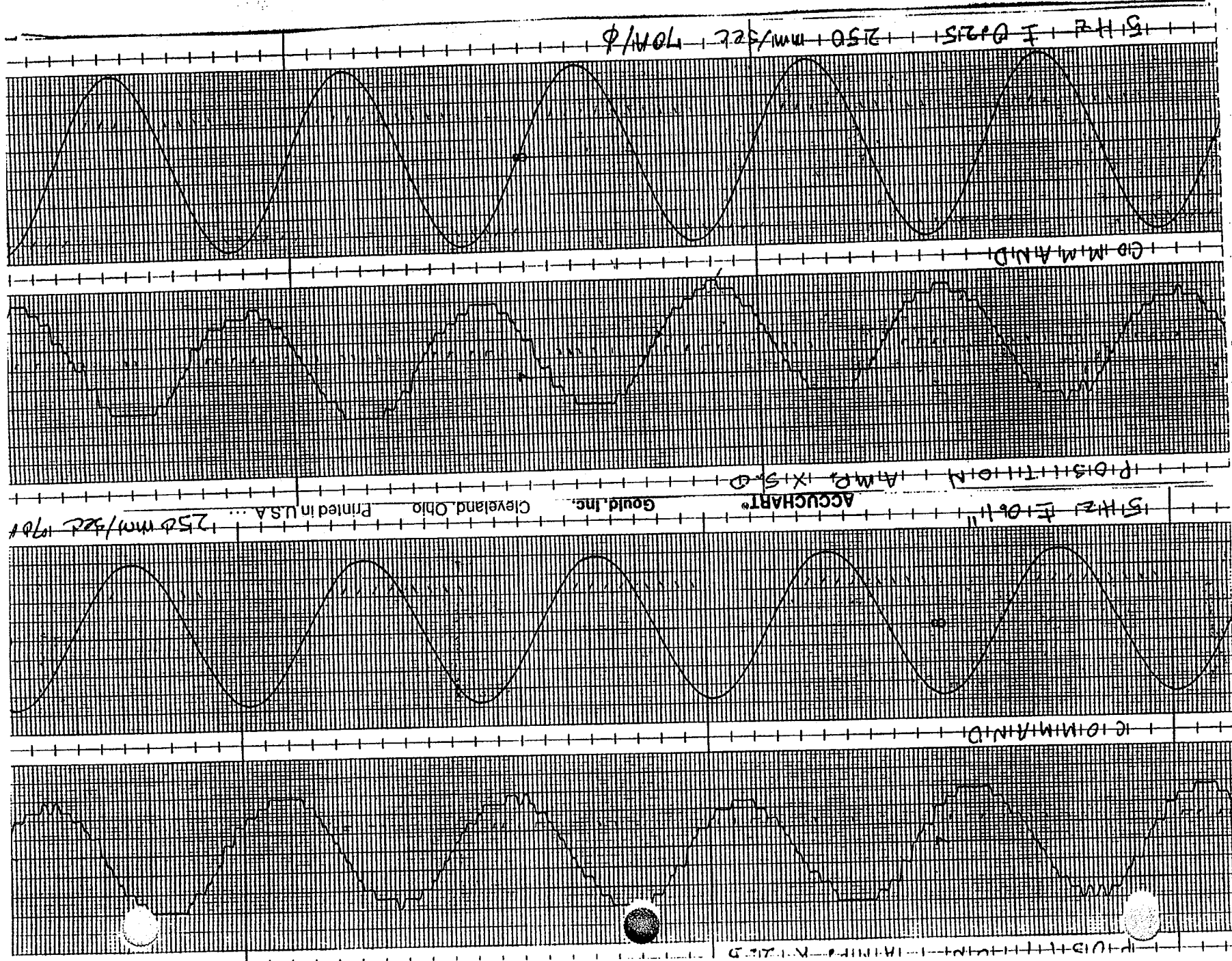
8-12-93

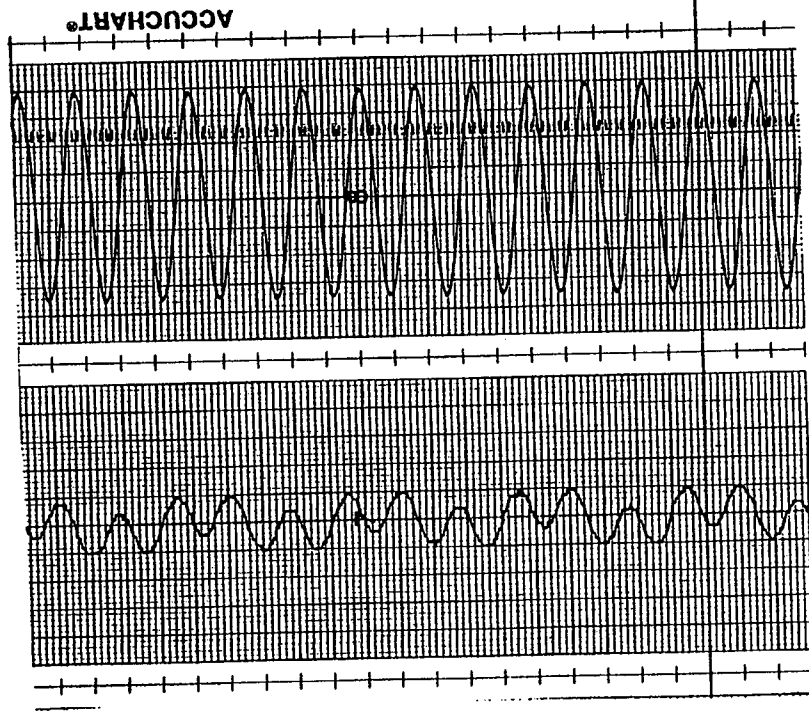


5.0 Hz ± 0.5 " 100/ ϕ 50mm/sec

Command

Position





6.0 HZ F 0.1" 10A/φ 50mm/sec

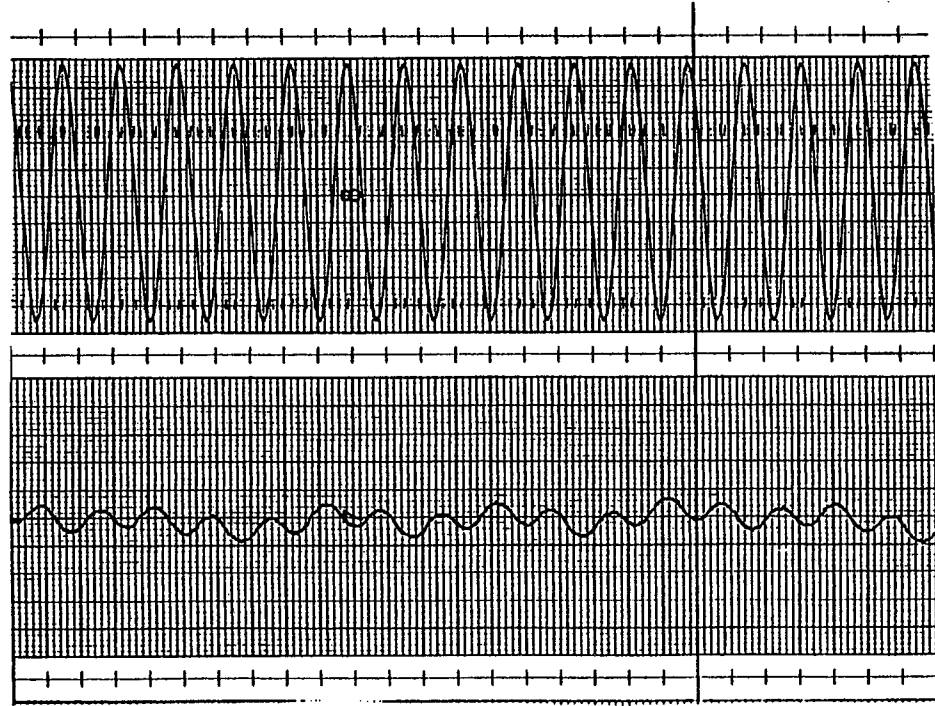
Command

Position

8-13-

Command

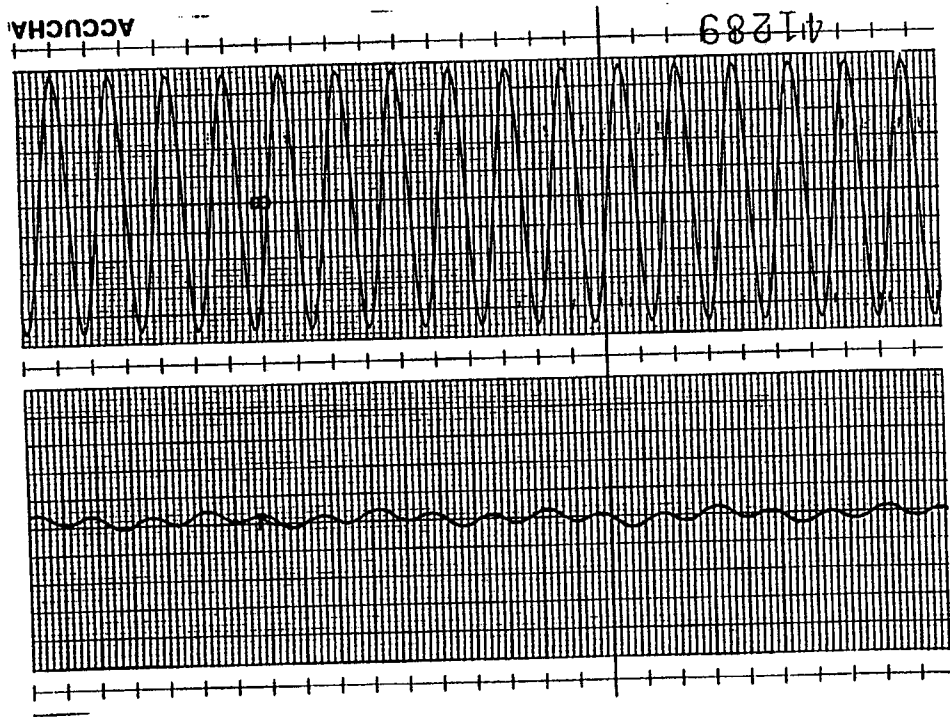
Position



6.0 Hz ± 0.25 " $70H/\phi$ 50mm/sec

8-13-93

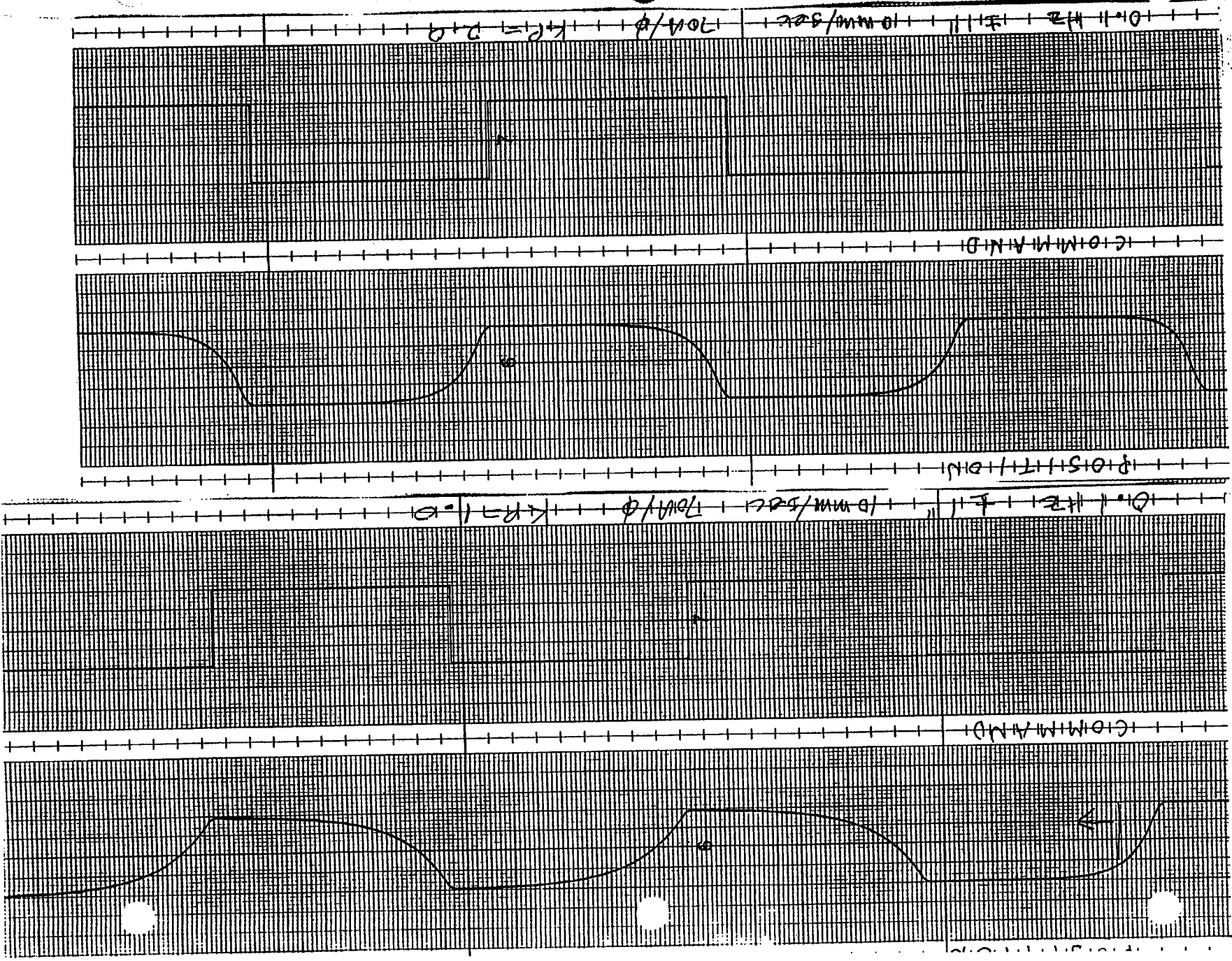
8-12-73



6.0 Hz \pm 0.5" 700 ϕ 500 m/sec

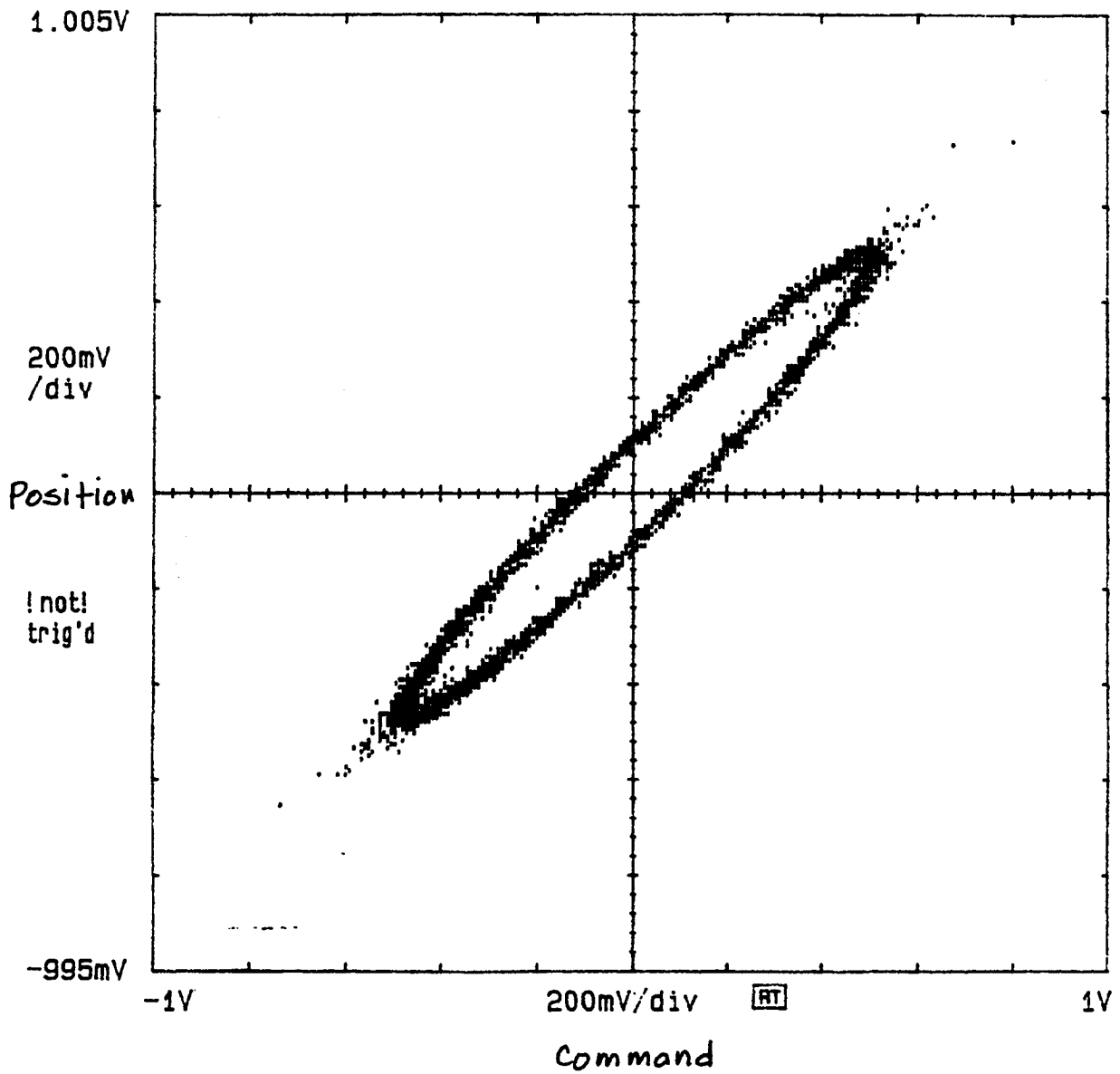
Command

Position



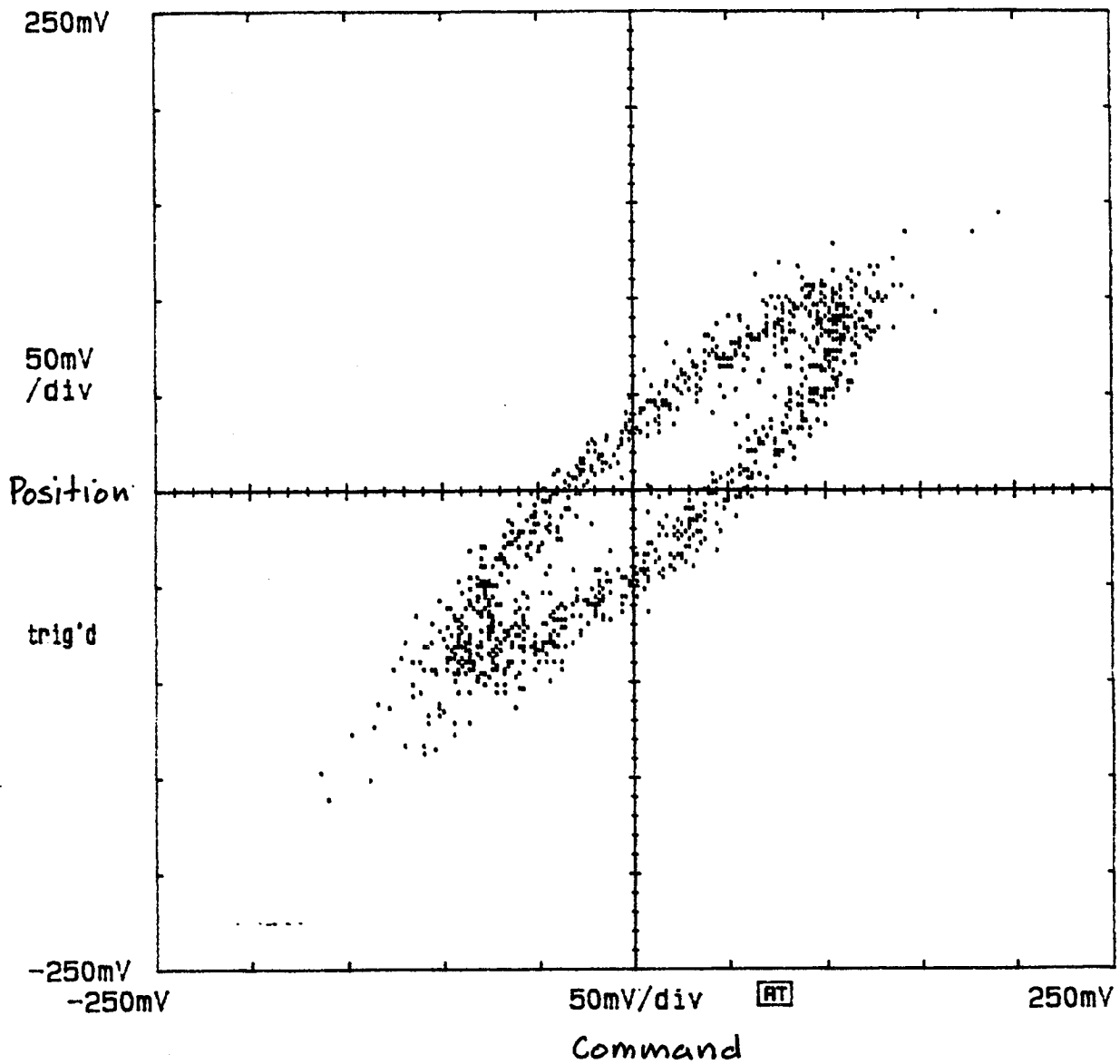
DSA 602 DIGITIZING SIGNAL ANALYZER

date: 23-AUG-93 time: 10:30:59



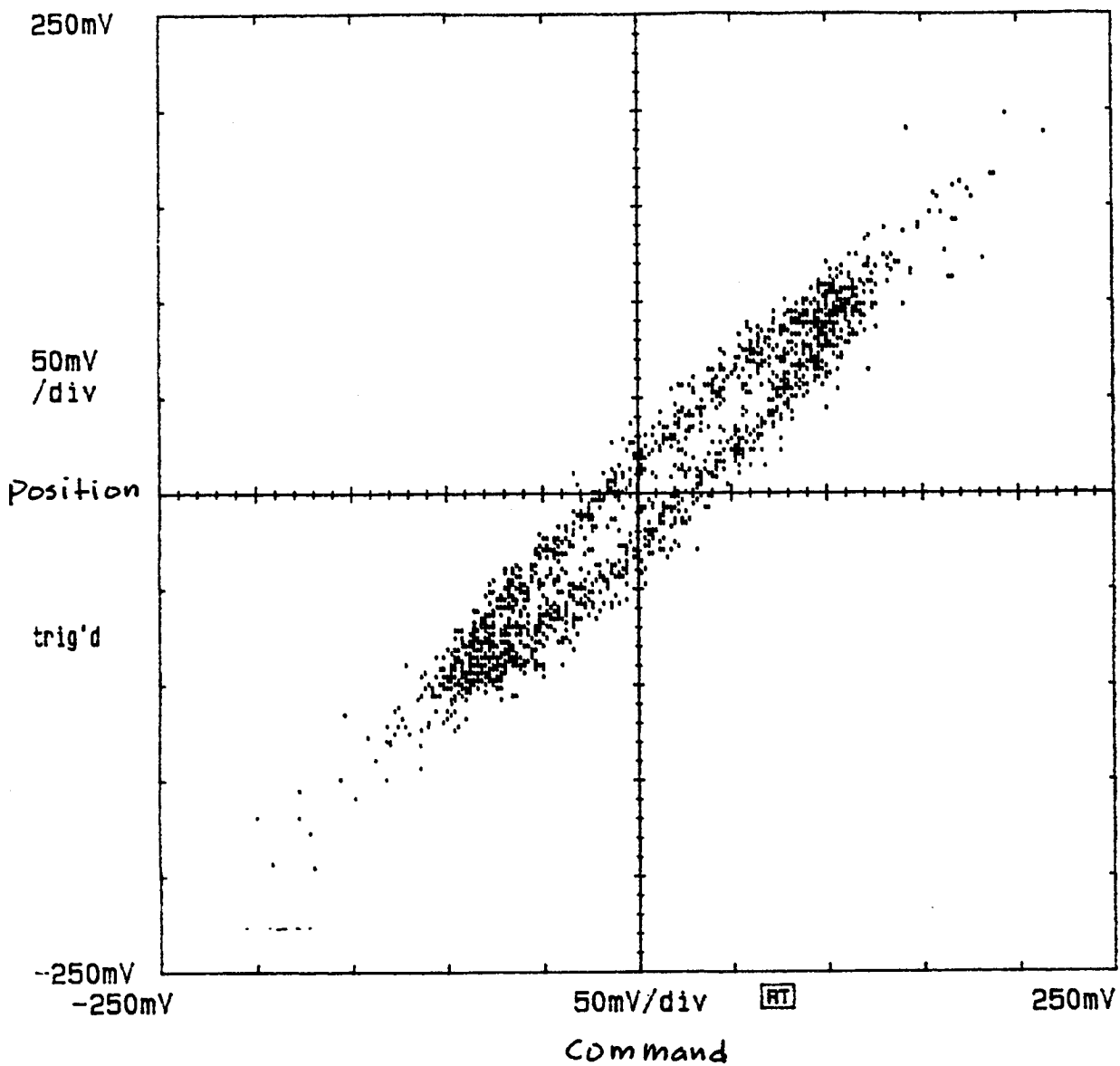
$0.5 \text{ Hz} \pm 0.5''$ $70 \pi / \phi$ $K_p = 14.3$

DSA 602 DIGITIZING SIGNAL ANALYZER
date: 23-AUG-93 time: 14:20:06



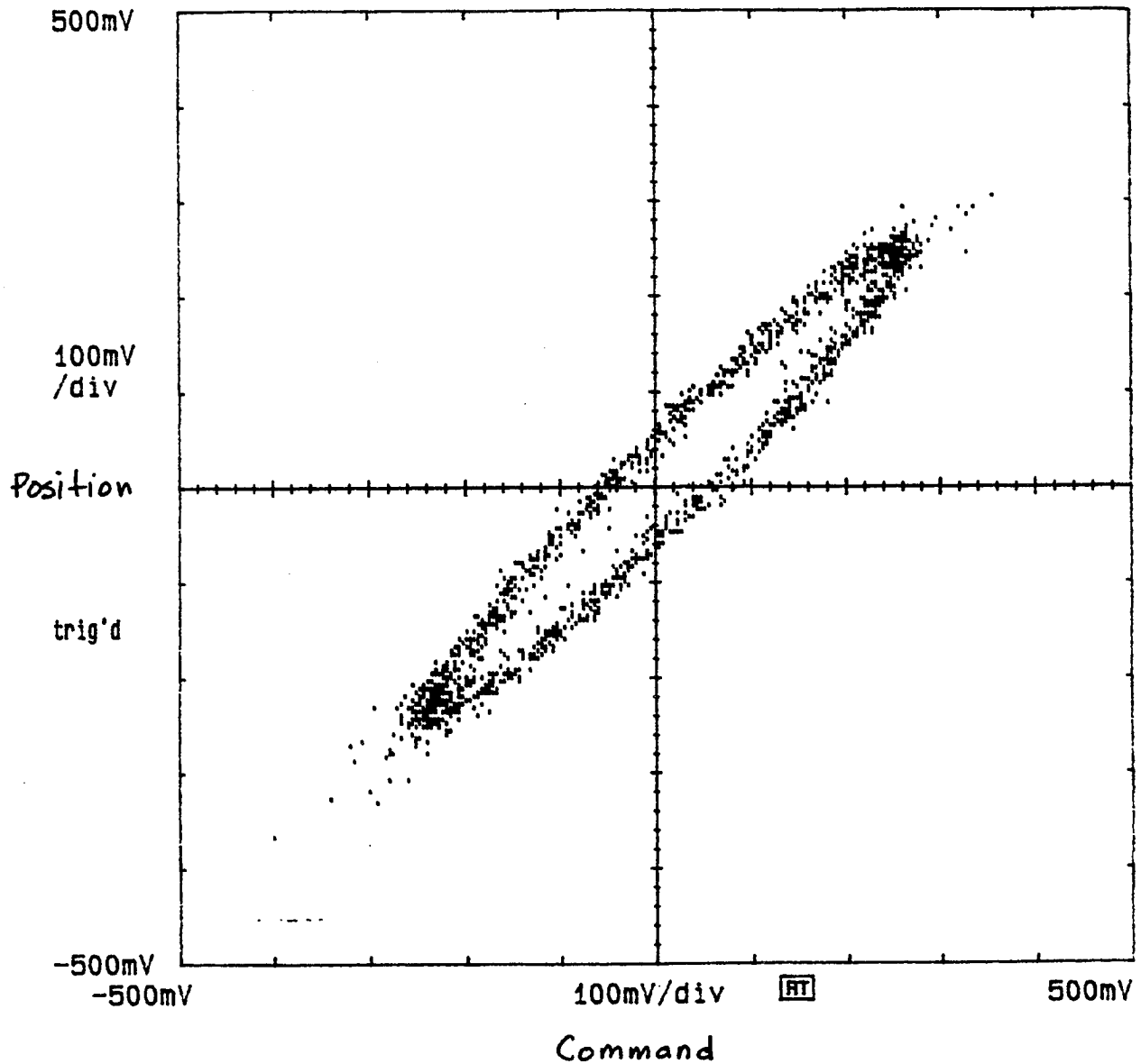
1.0 Hz $\pm 0.1''$ 70A/ ϕ $k_p = 14.3$

DSA 602 DIGITIZING SIGNAL ANALYZER
date: 23-AUG-93 time: 14:26:27



0.5Hz $\pm 0.1''$ 70A/ ϕ Kp = 14.3

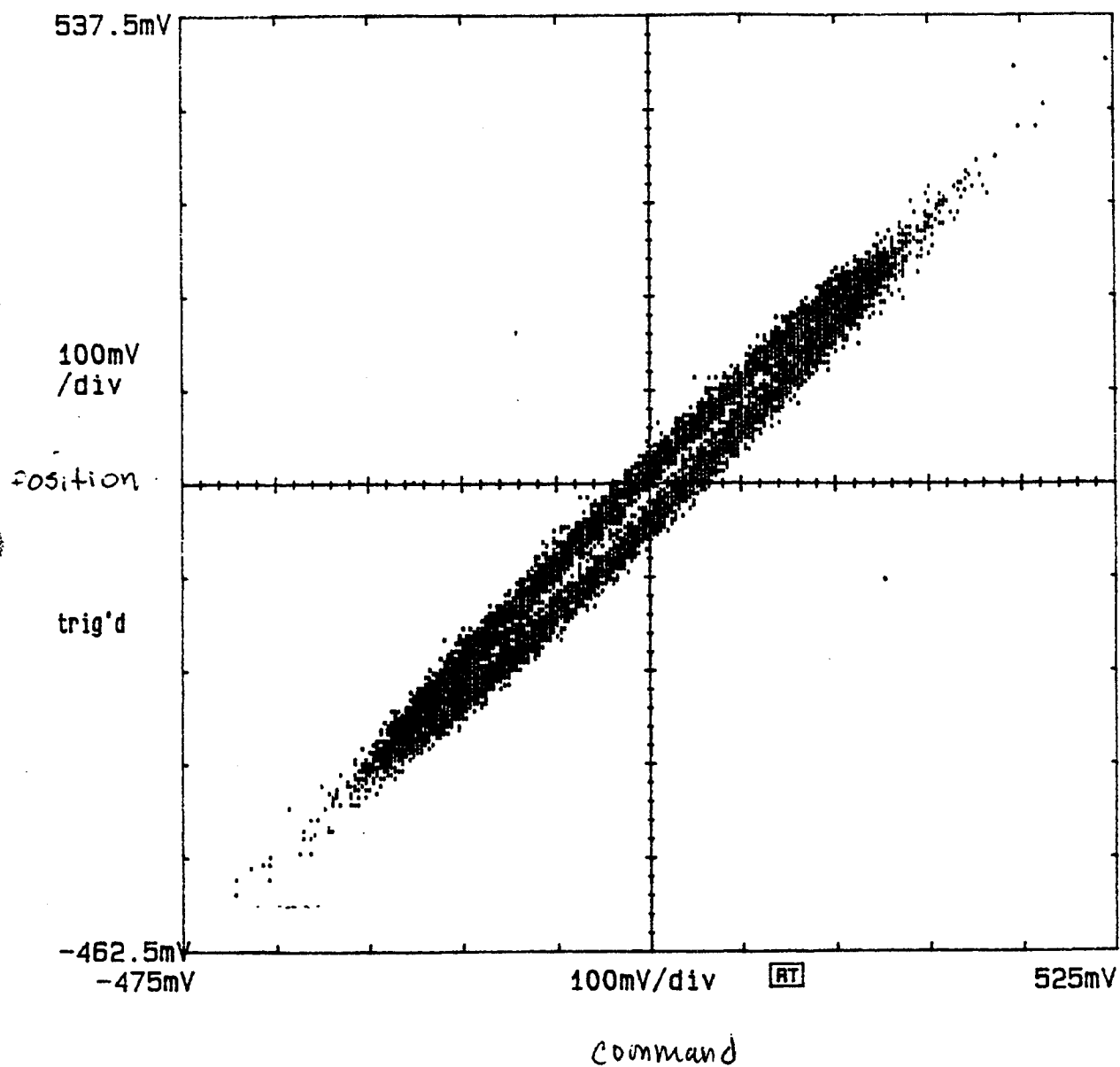
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 23-AUG-93 time: 14:34:05



$0.5 \text{ Hz} \pm 0.25''$ $70 \text{ A}/\phi$ $K_p = 14.3$

DSA 602 DIGITIZING SIGNAL ANALYZER

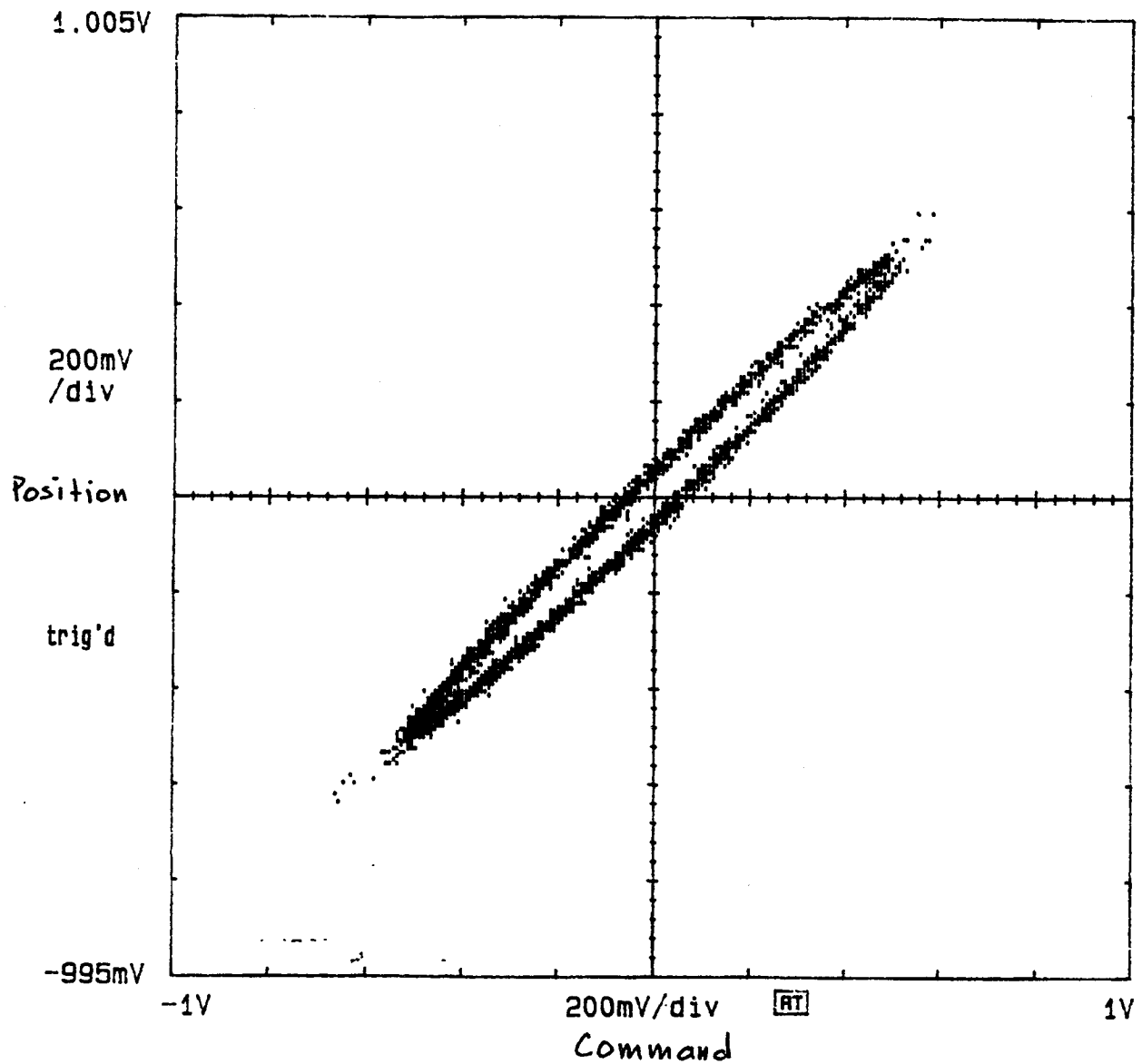
date: 23-AUG-93 time: 10:06:33



0.25 Hz $\pm 0.25''$ 70A/ ϕ KP=14.3

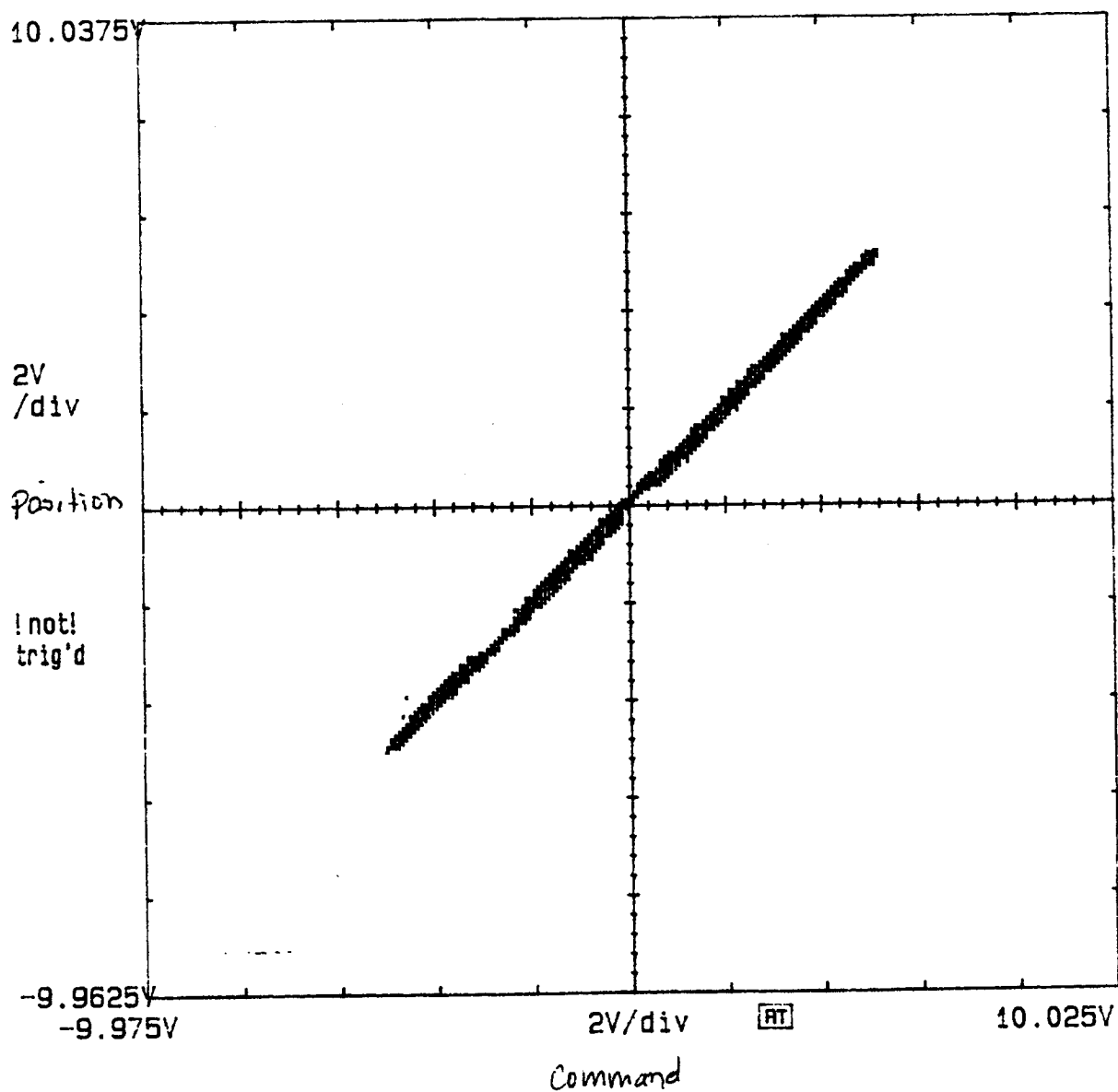
DSA 602 DIGITIZING SIGNAL ANALYZER

date: 23-AUG-93 time: 10:21:25



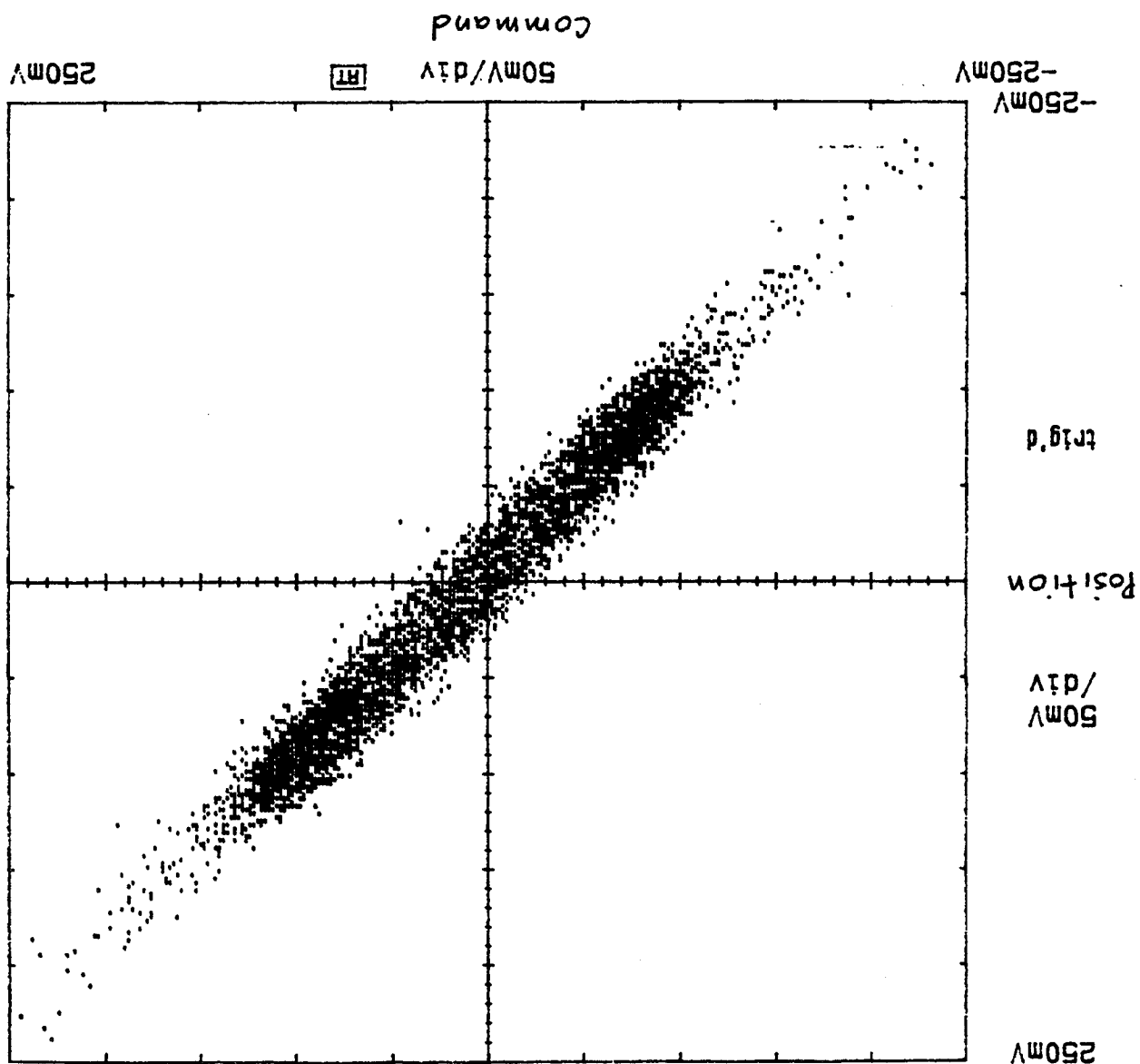
0.25 Hz $\pm 0.5''$ 70 A/ ϕ $k_p = 14.3$

DSA 602 DIGITIZING SIGNAL ANALYZER
date: 23-AUG-93 time: 9:52:16



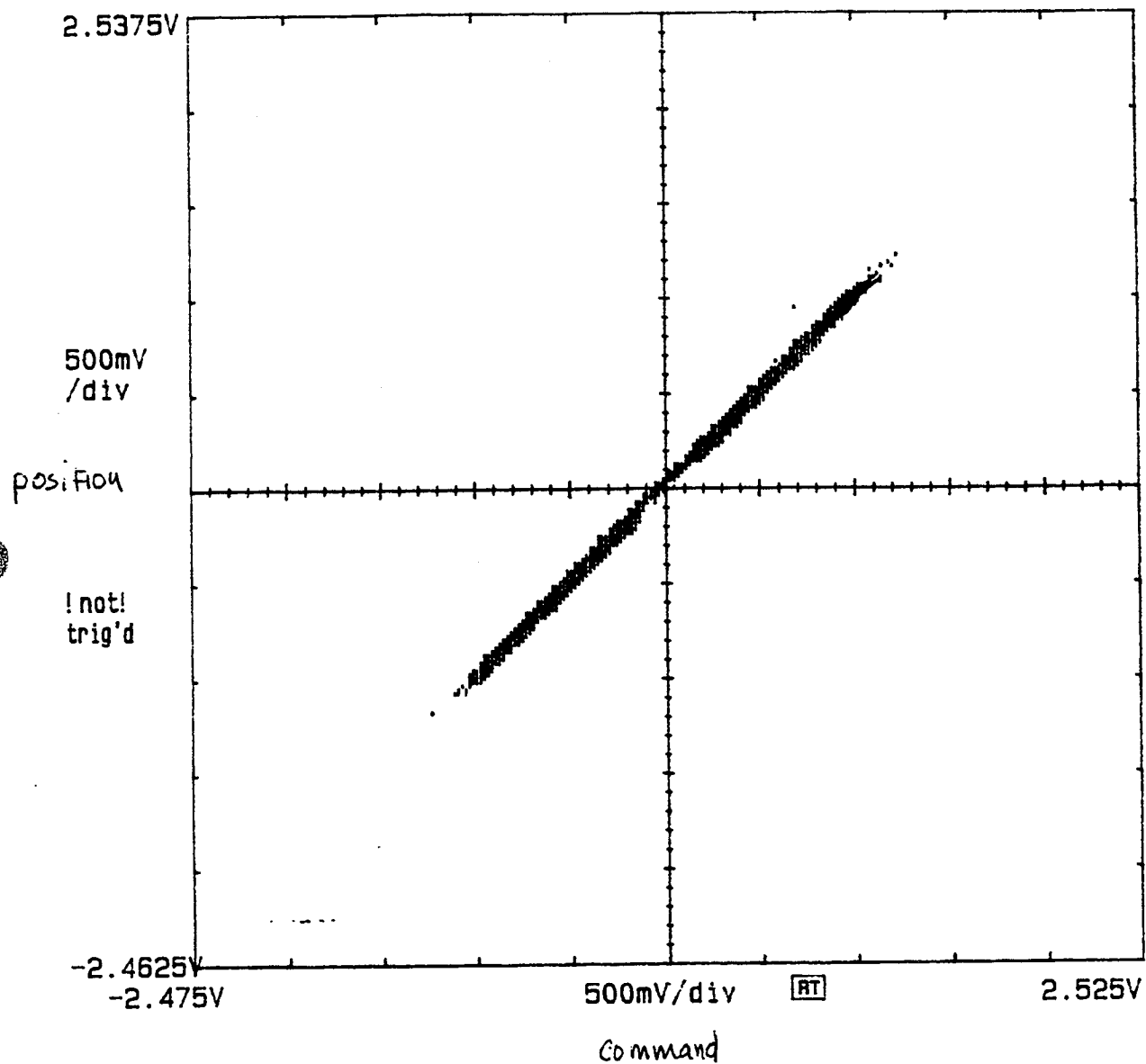
0.05 Hz $\pm 5.0''$ 70A/ ϕ K ρ = 14.3

0.25 Hz $\pm 0.1''$ 70K/φ KP = 14.3



DSA 602 DIGITIZING SIGNAL ANALYZER
date: 23-AUG-93 time: 14:41:41

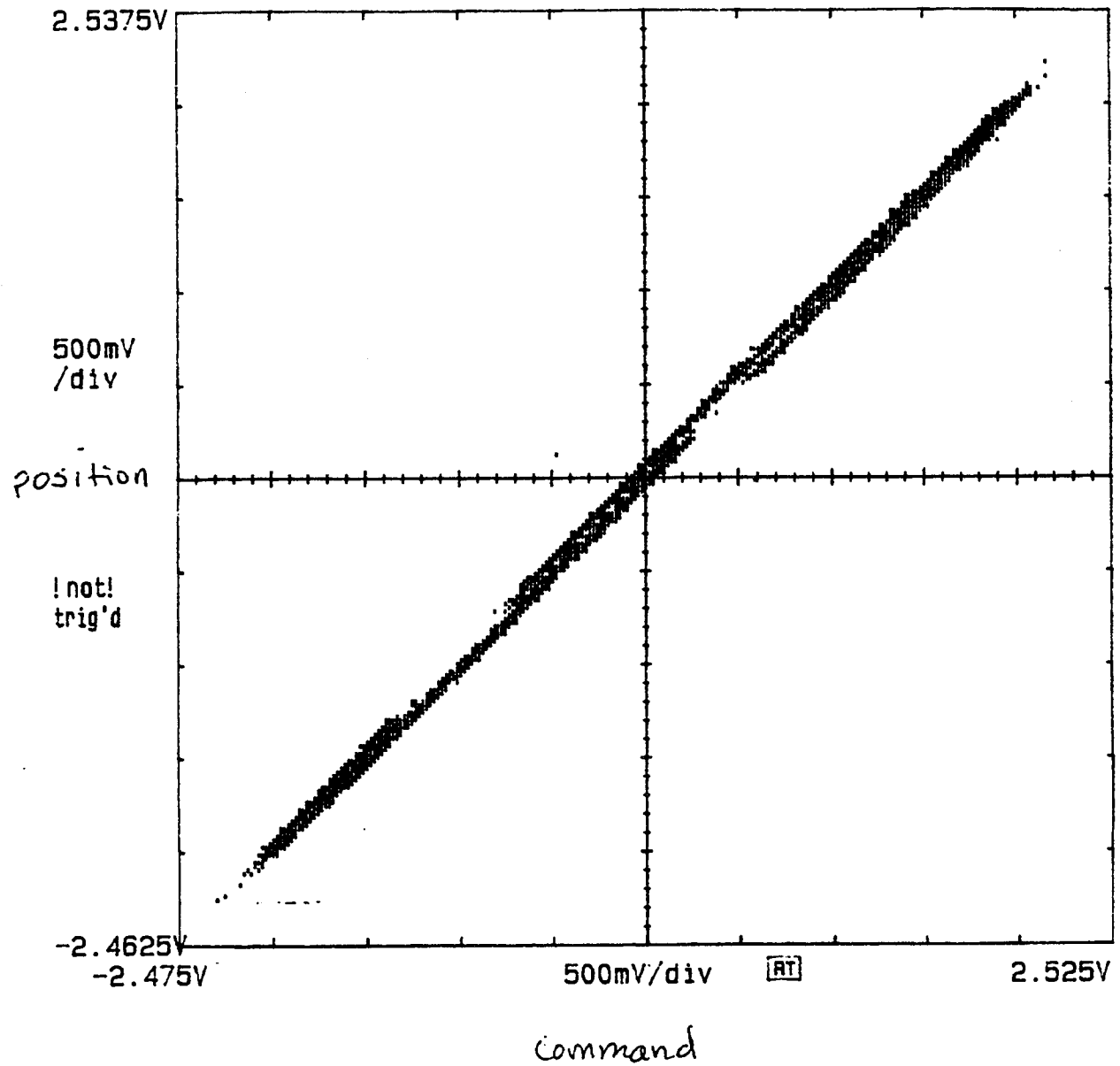
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 23-AUG-93 time: 9:38:23



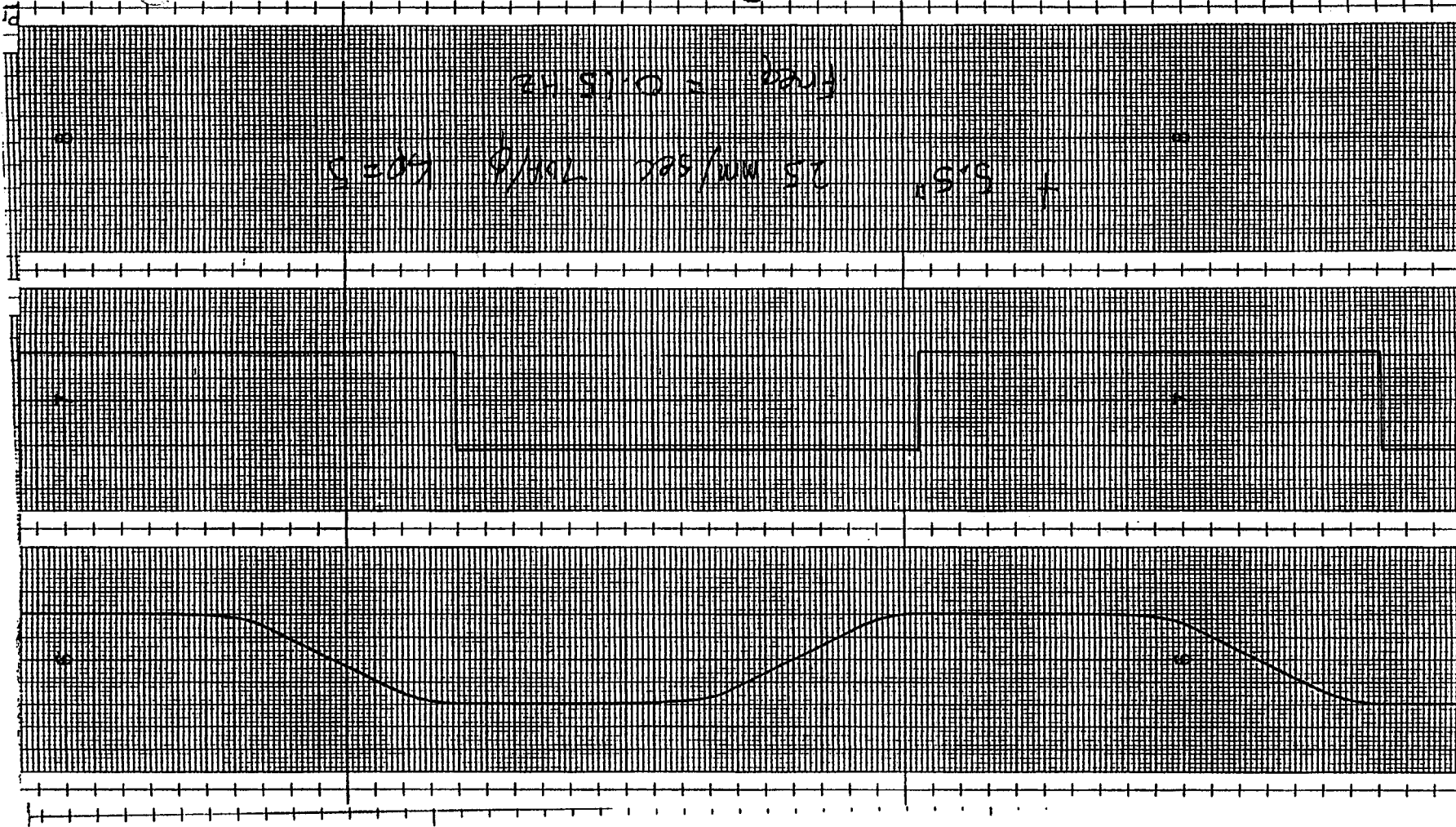
0.05 Hz $\pm 1.0^{\circ}$ 70A/ ϕ Kp=14.3

DSA 602 DIGITIZING SIGNAL ANALYZER

date: 23-AUG-93 time: 9:43:55



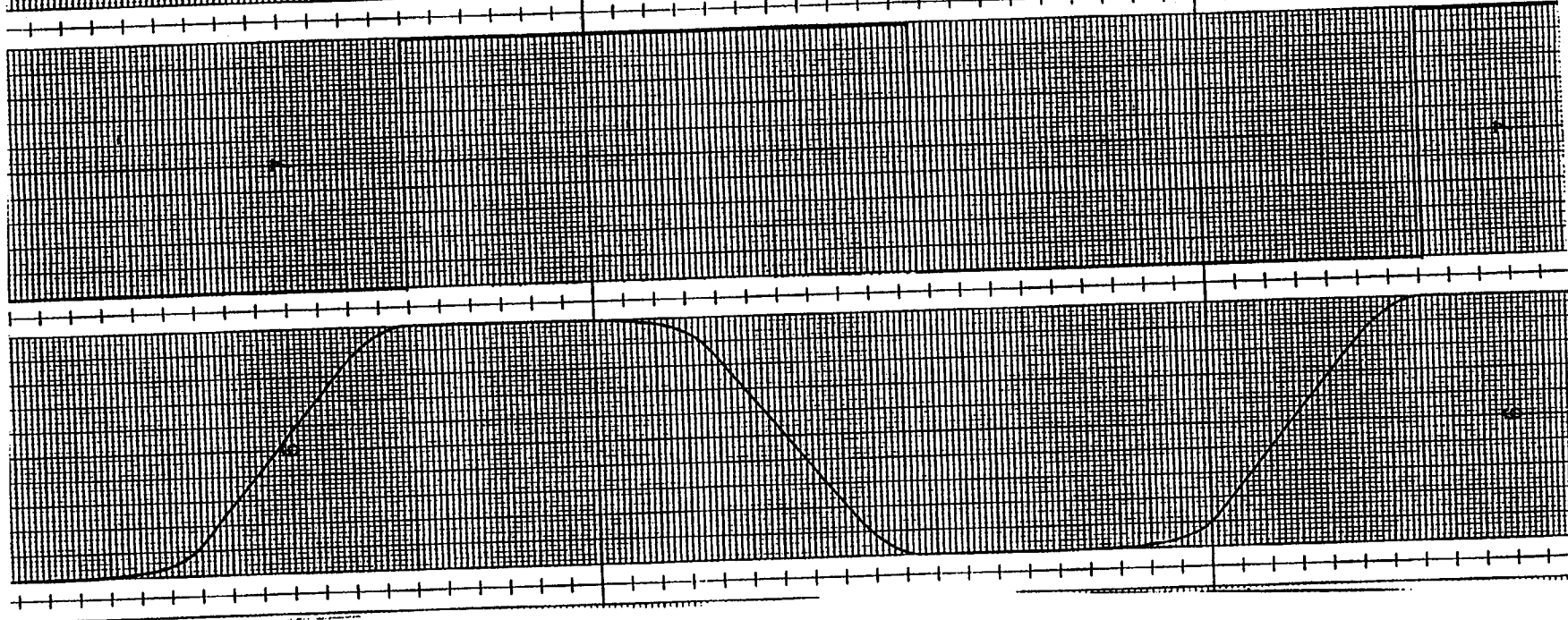
0.05 Hz $\pm 2.0''$ 70K/φ Kp = 14.3

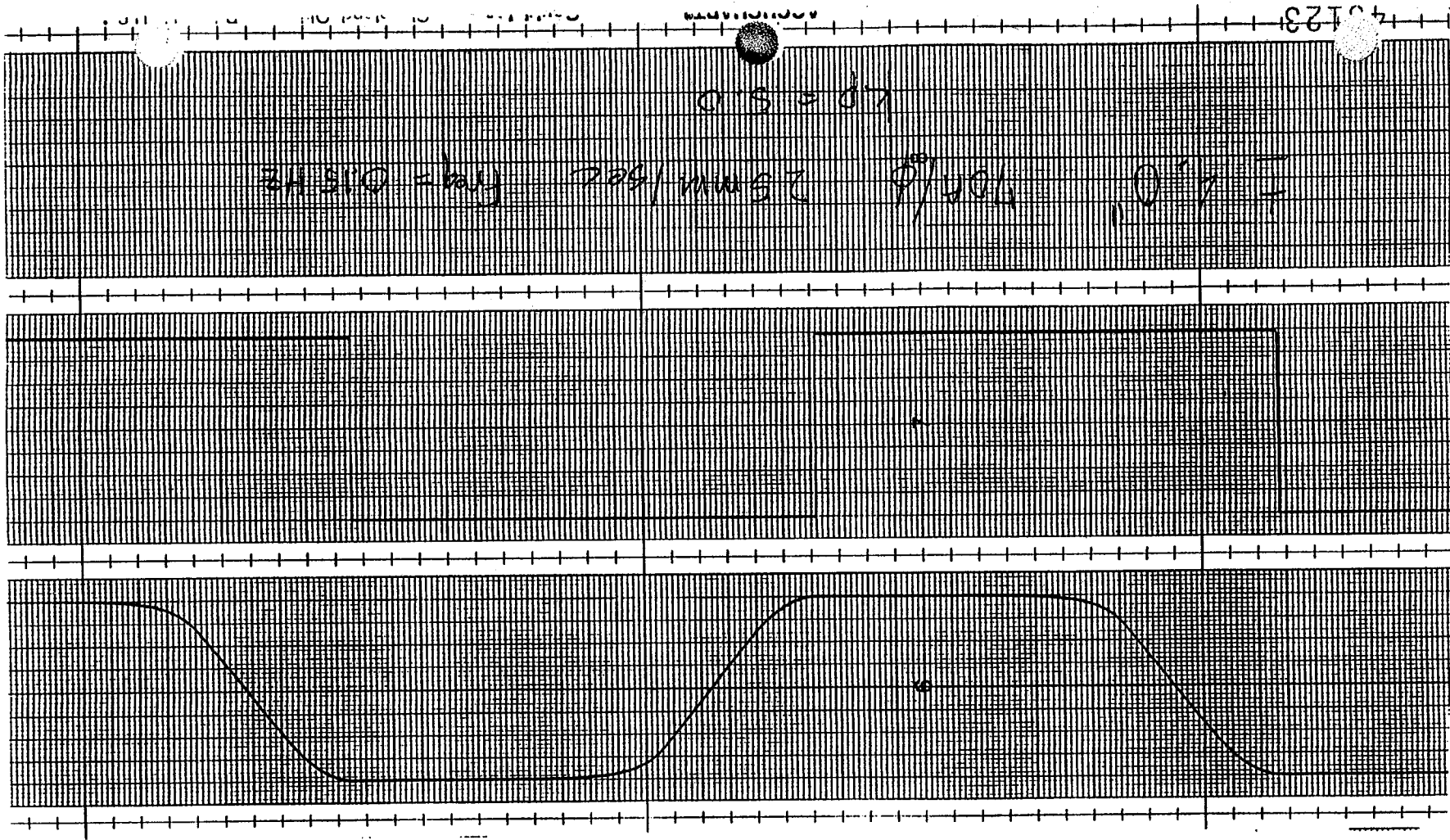


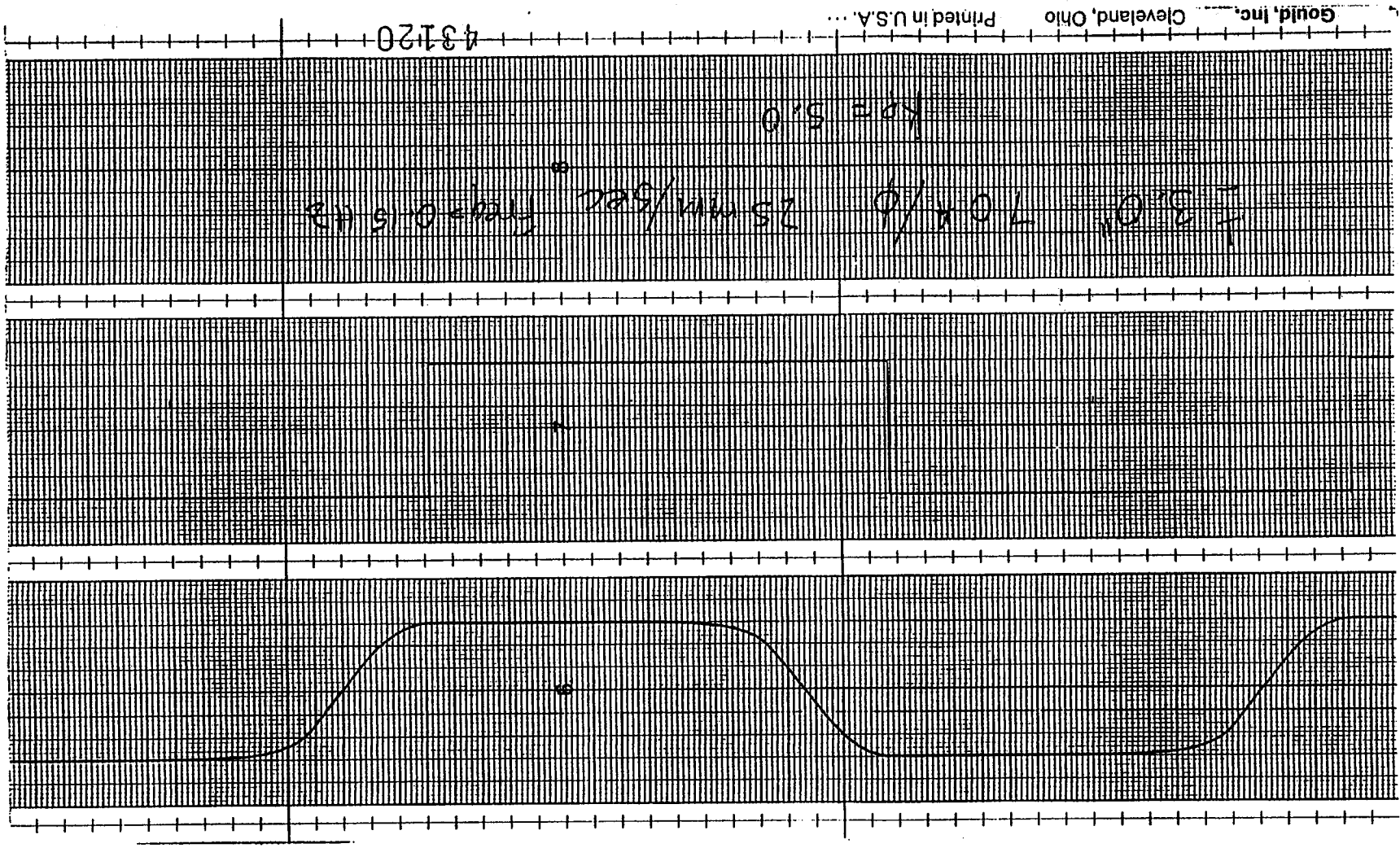
48127

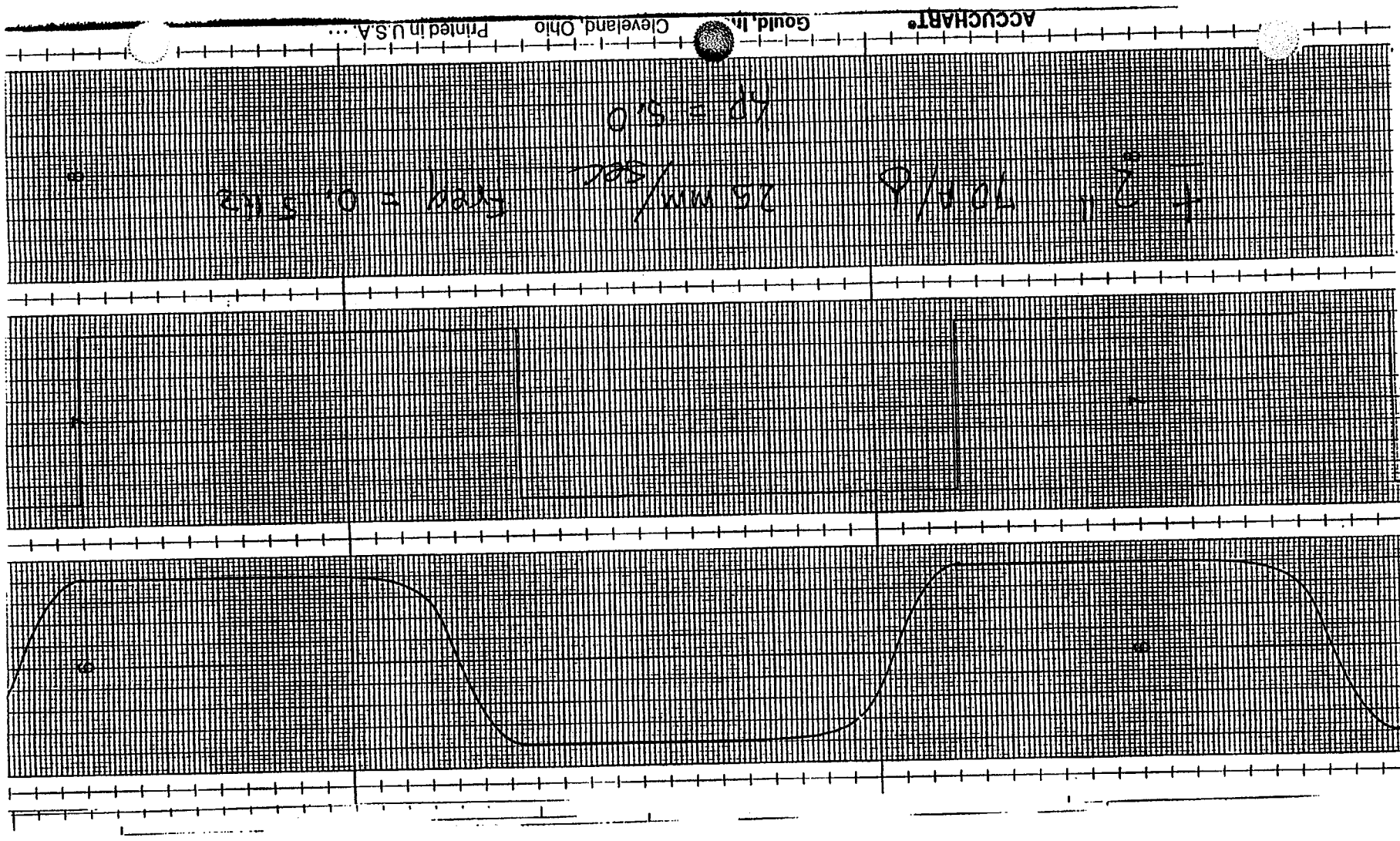
0.5 = 0.5

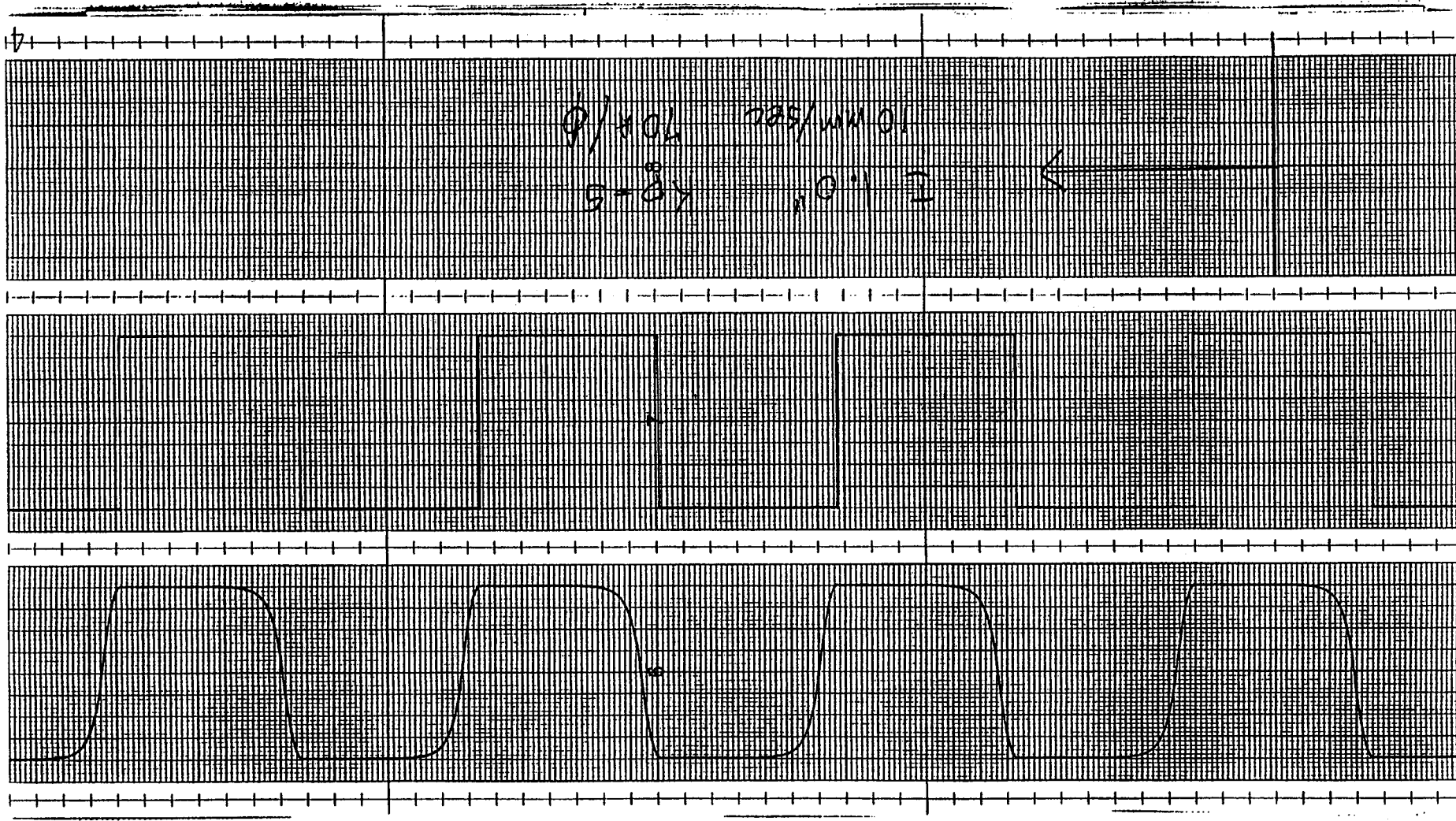
15.0 100/0 25mm/sec 1000 = 0.5 Hz

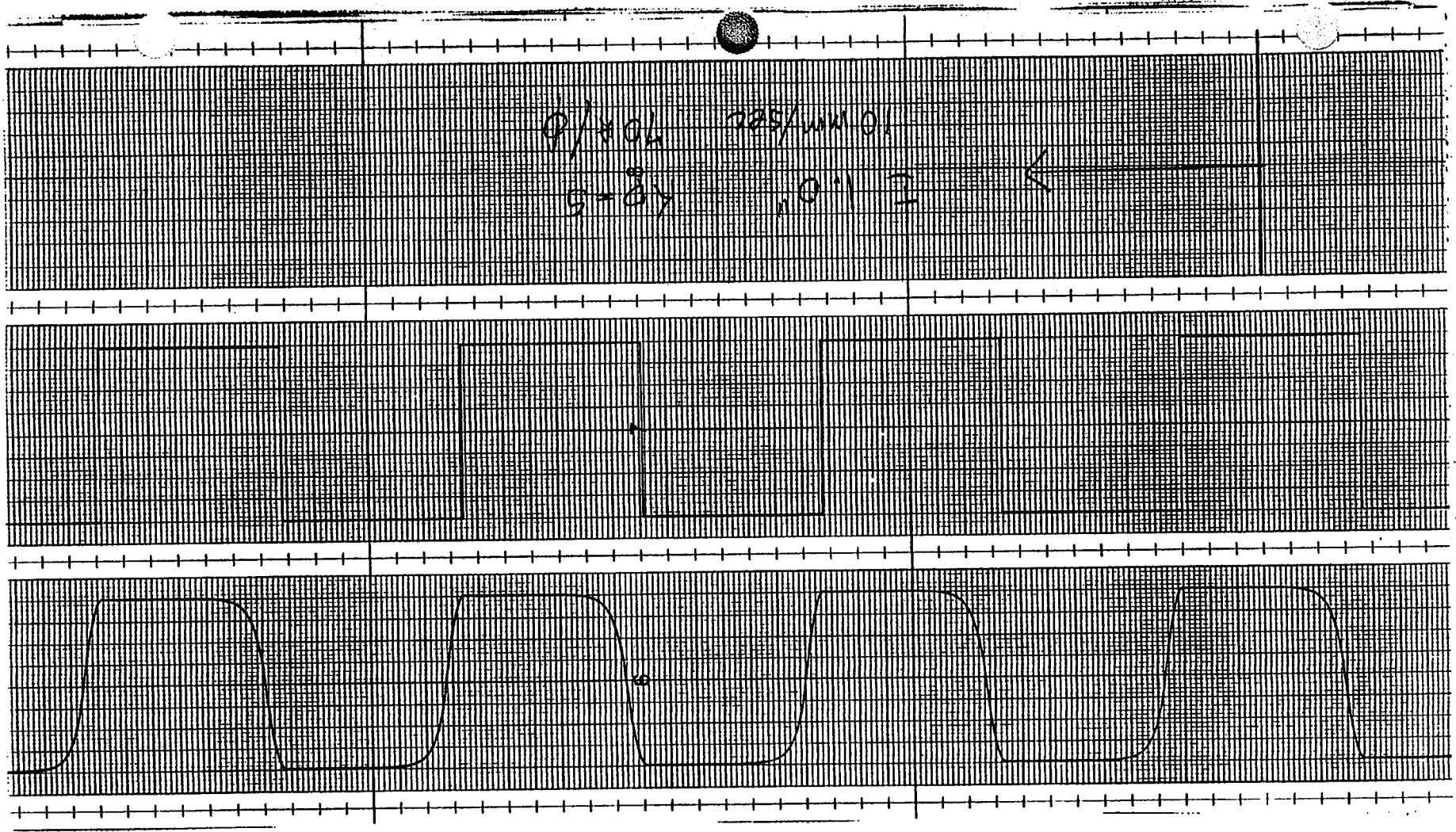


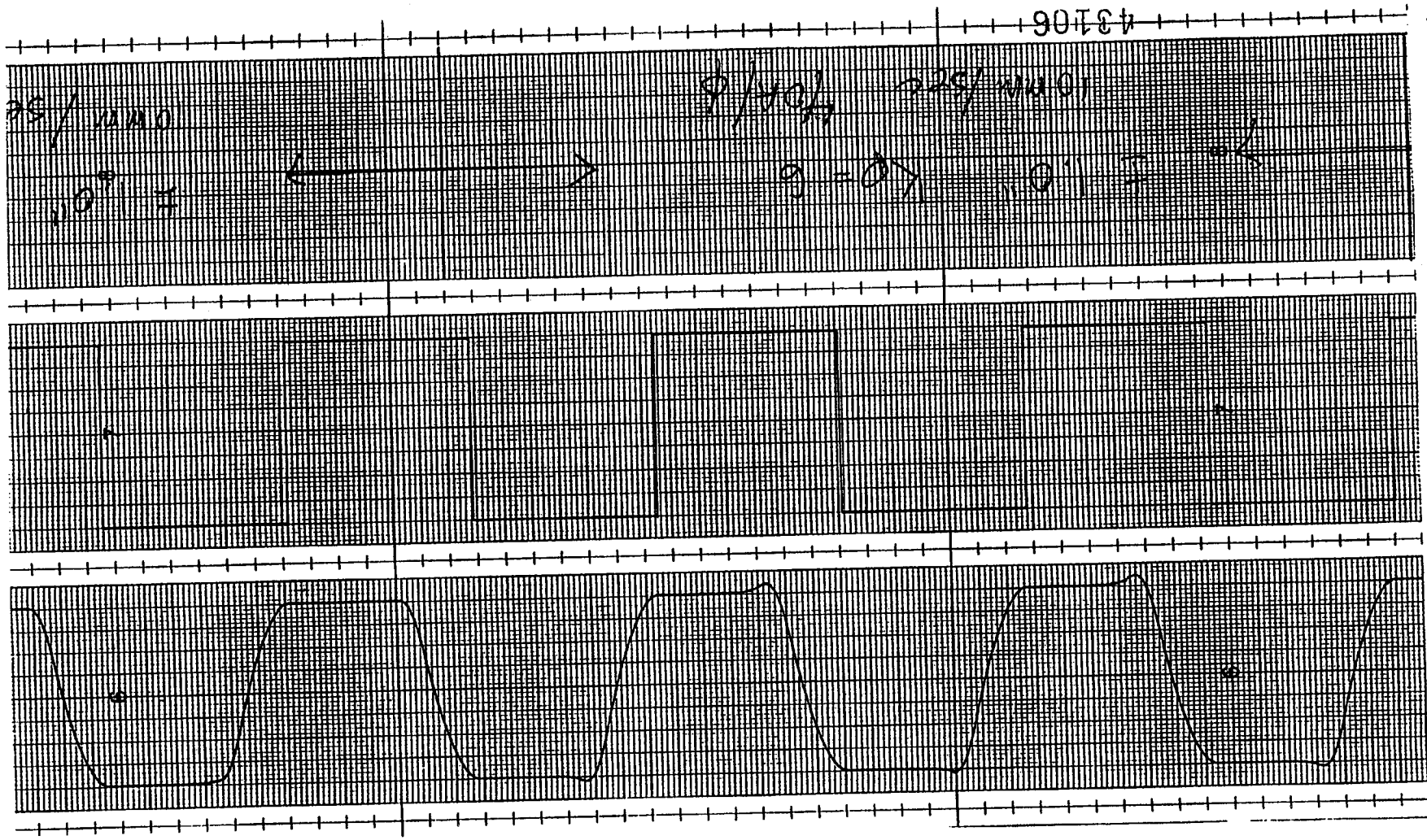


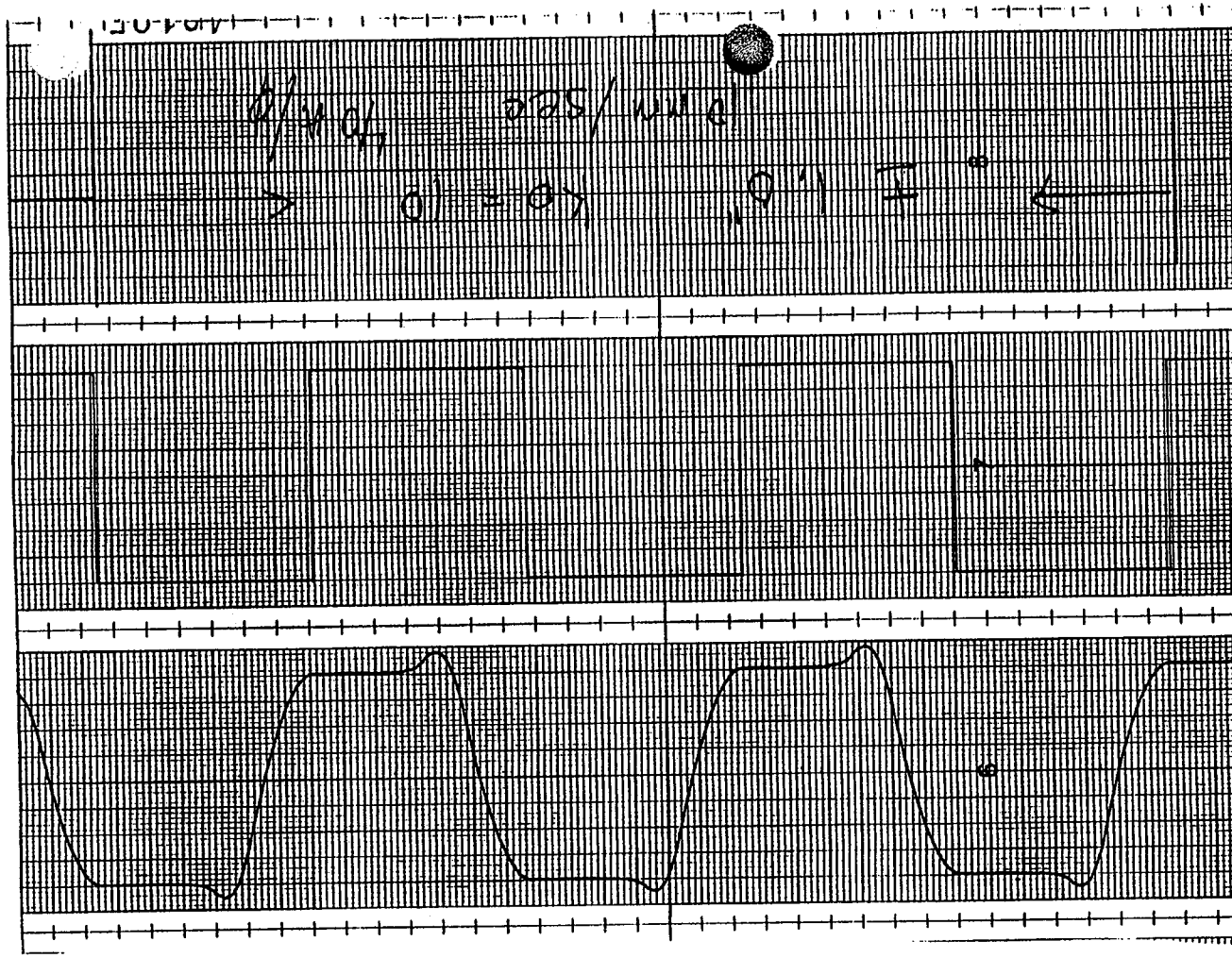


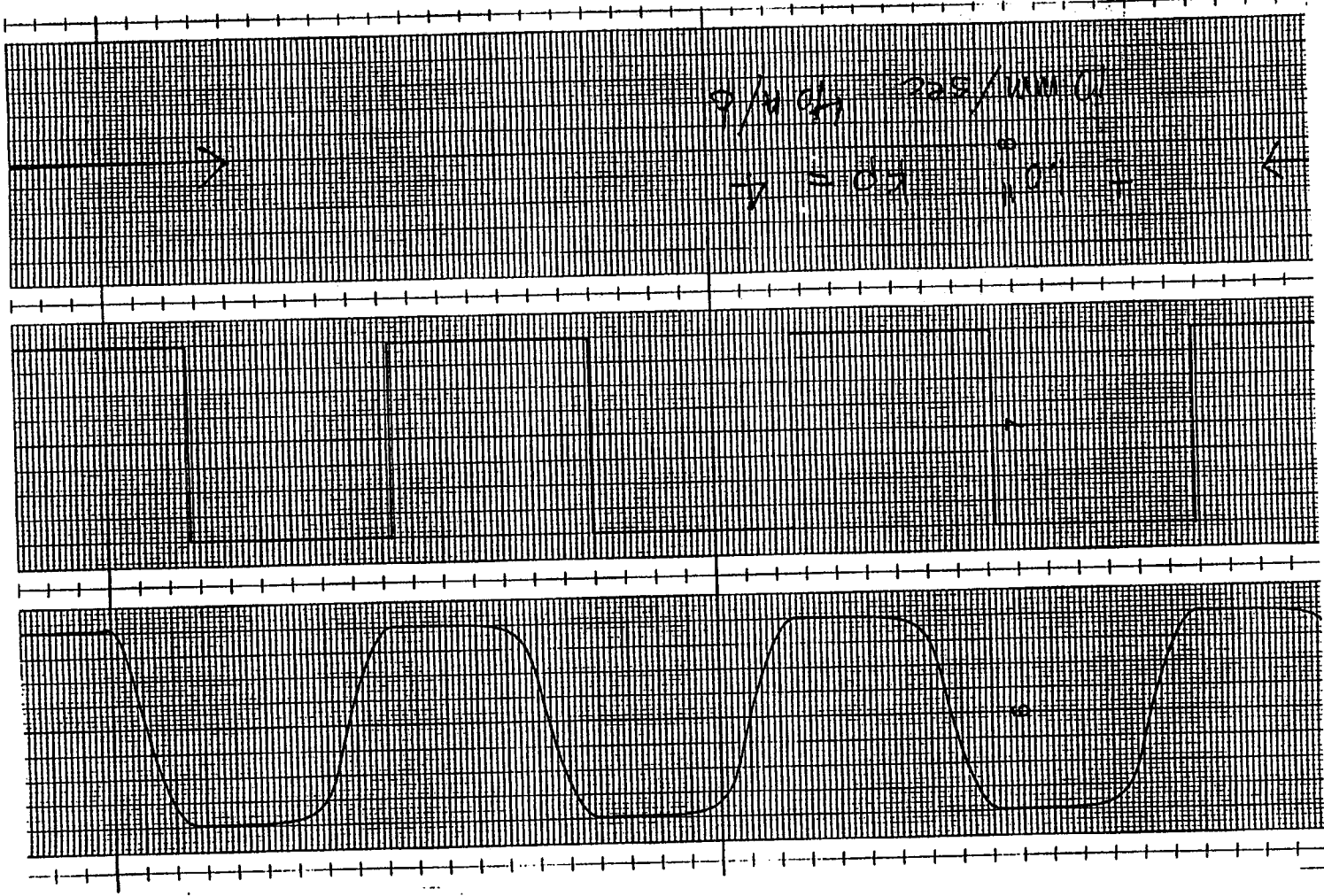


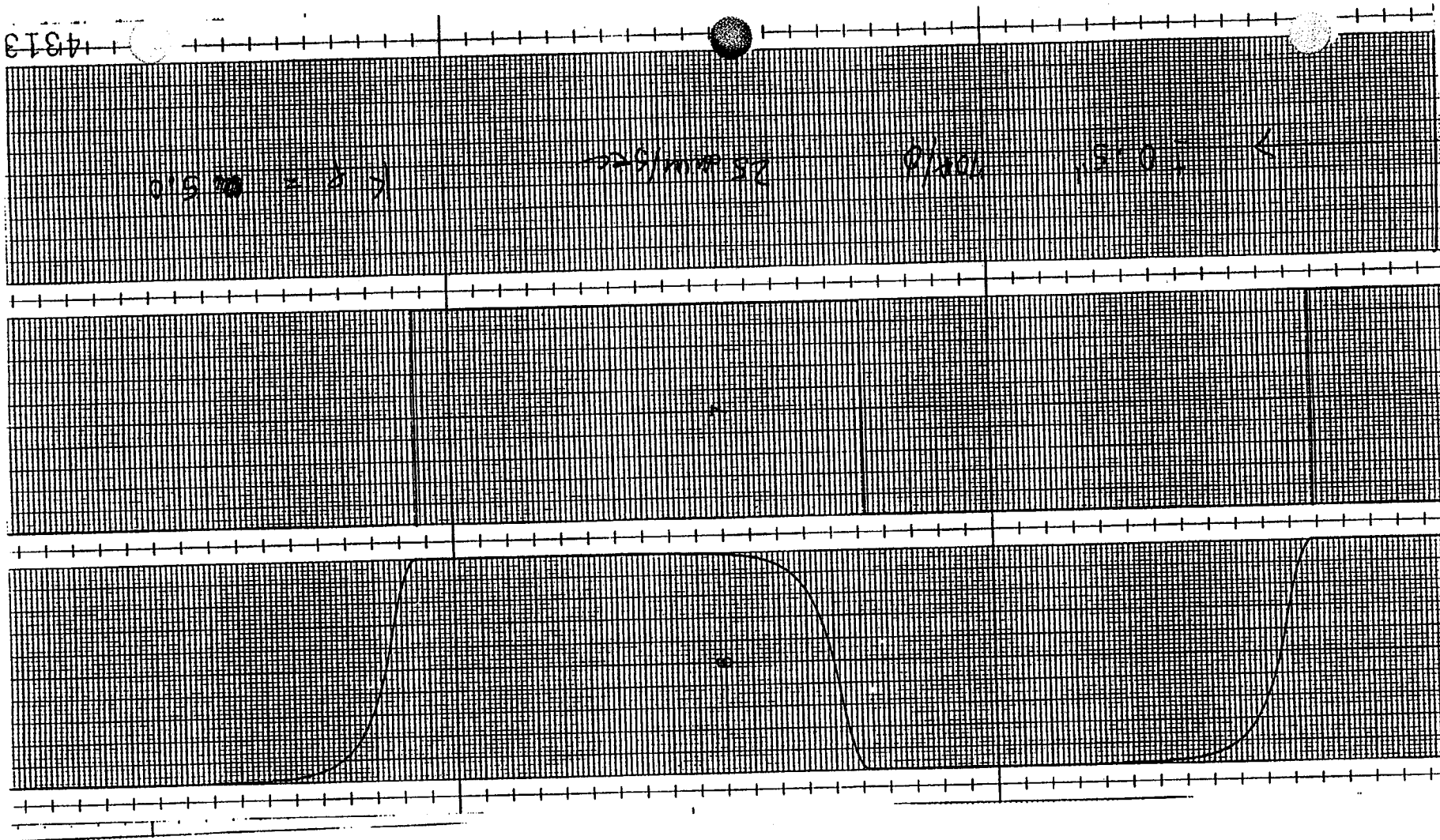


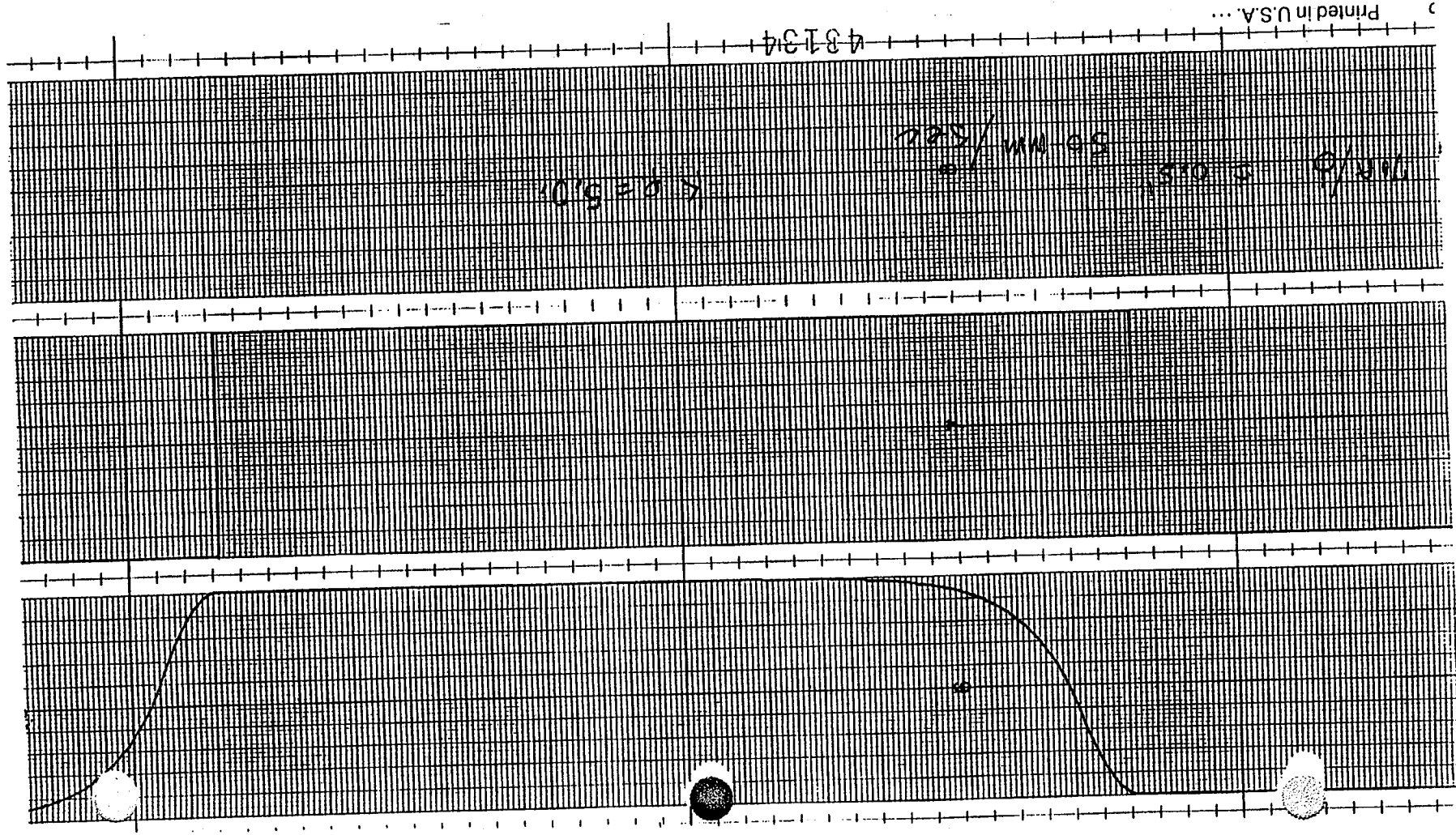


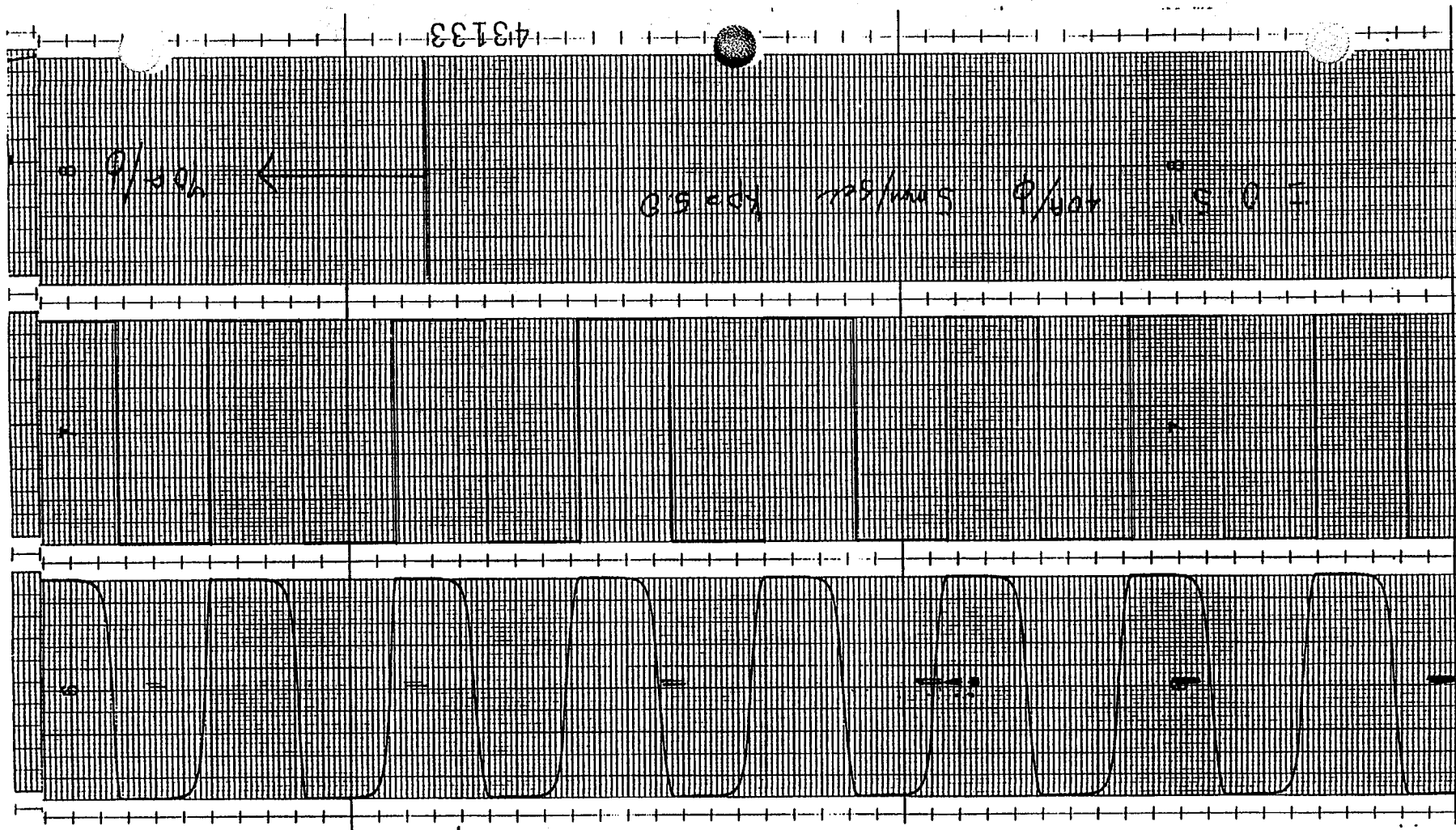


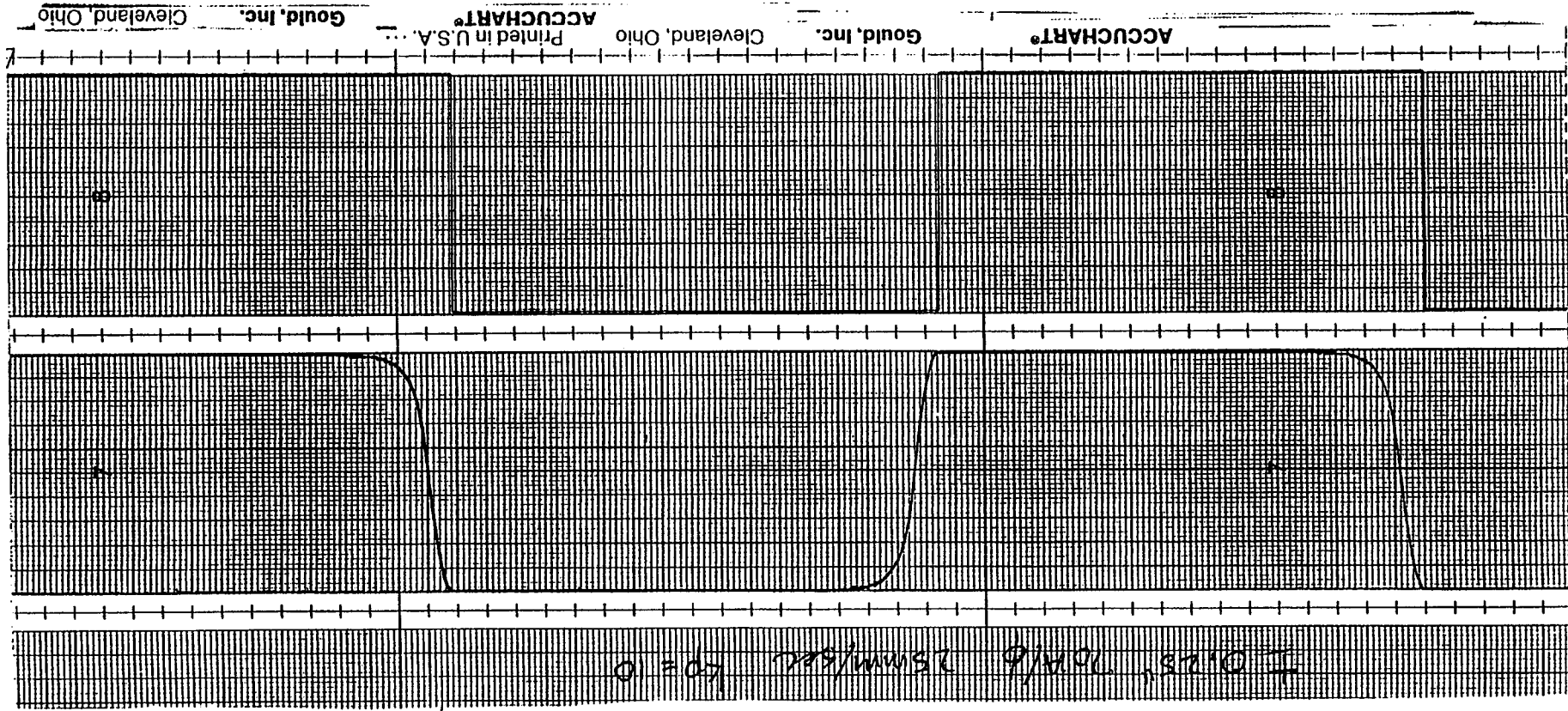


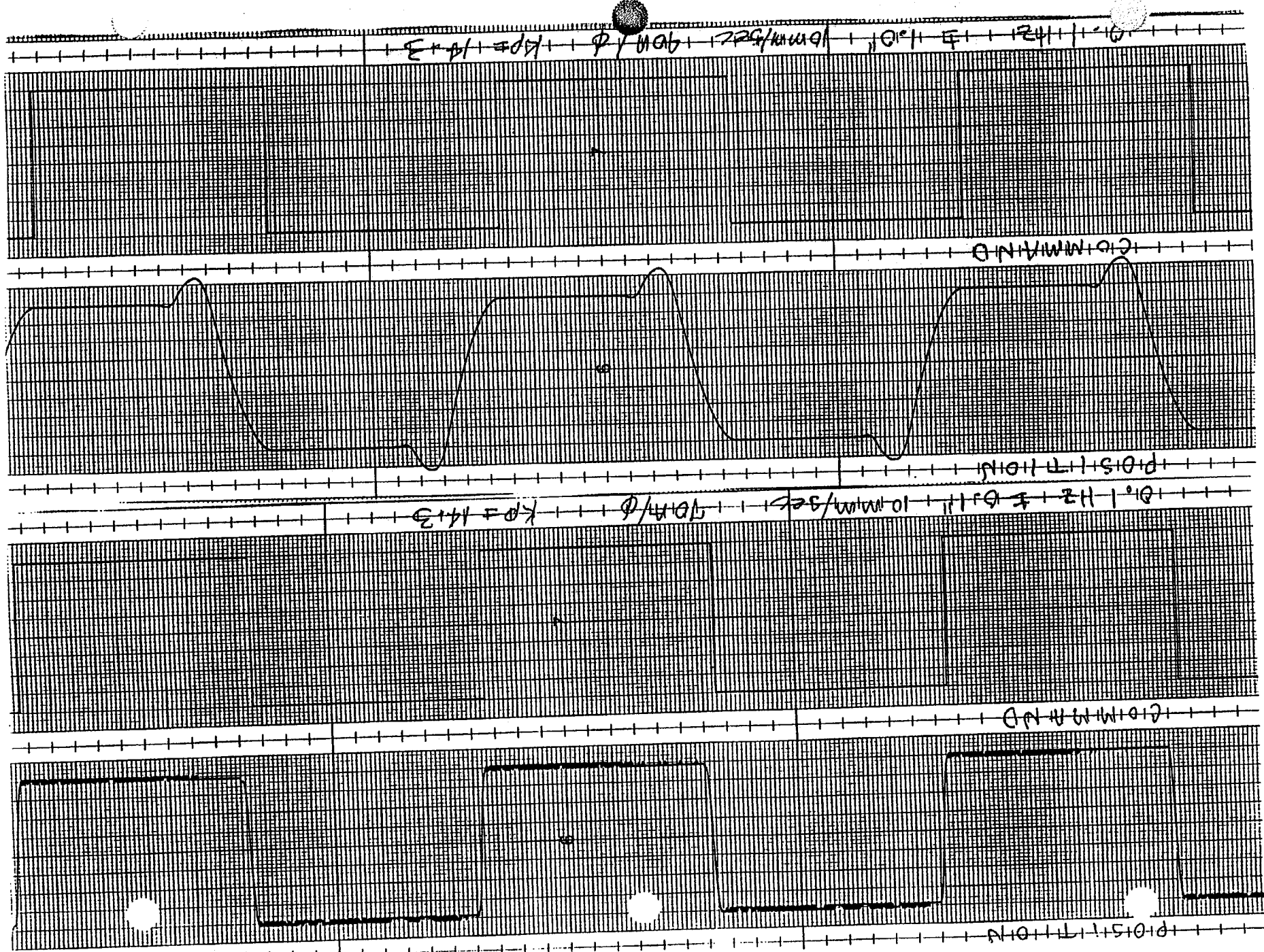


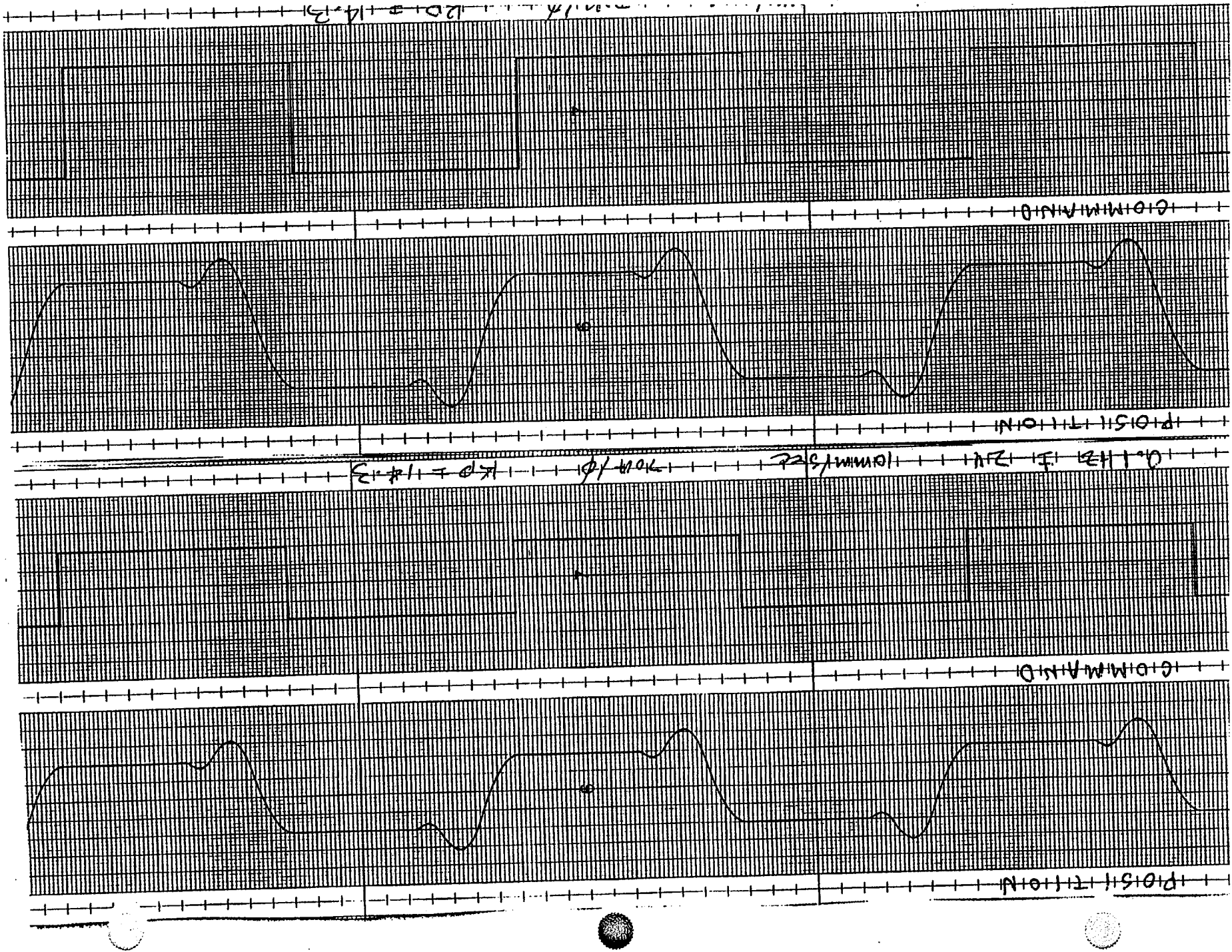


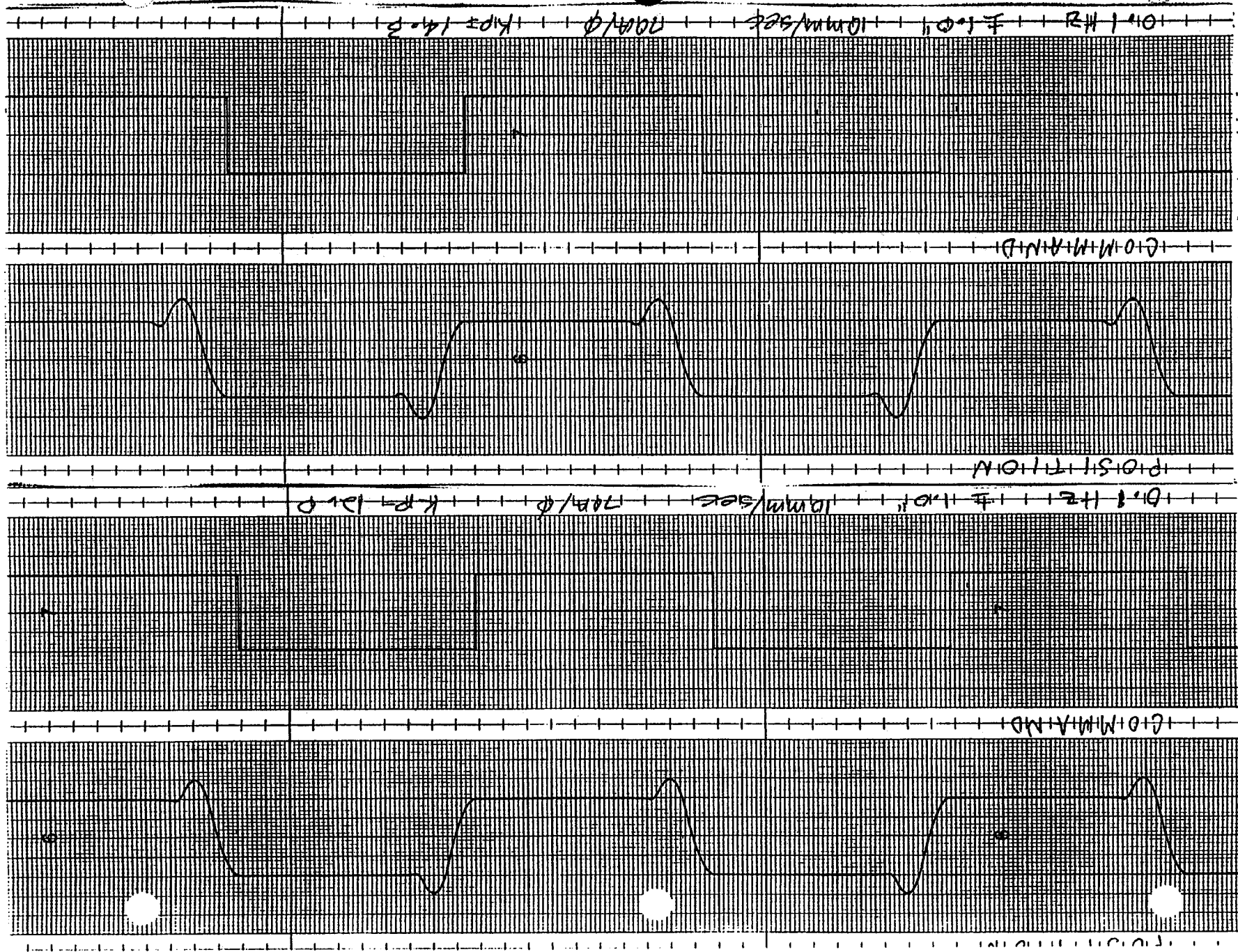


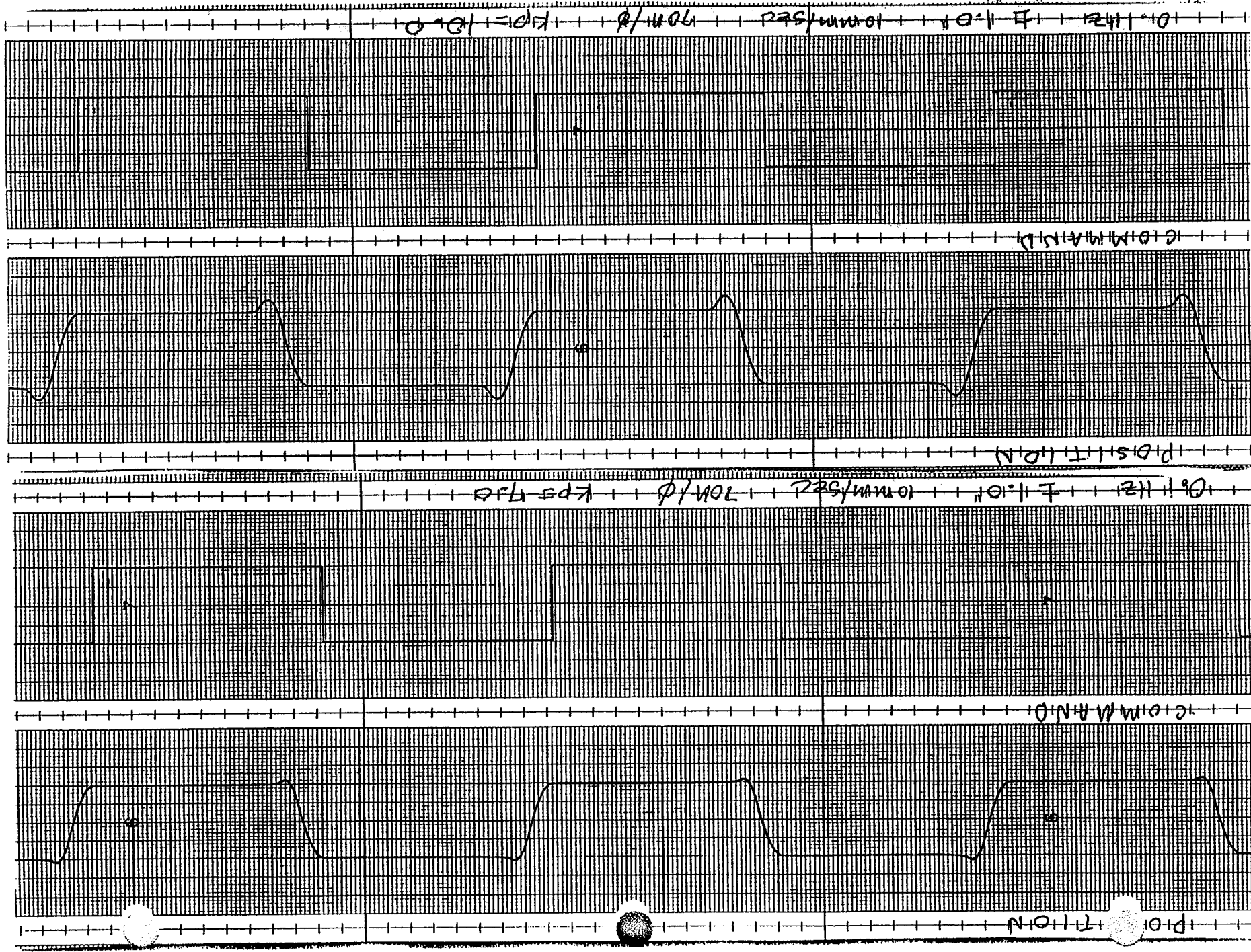


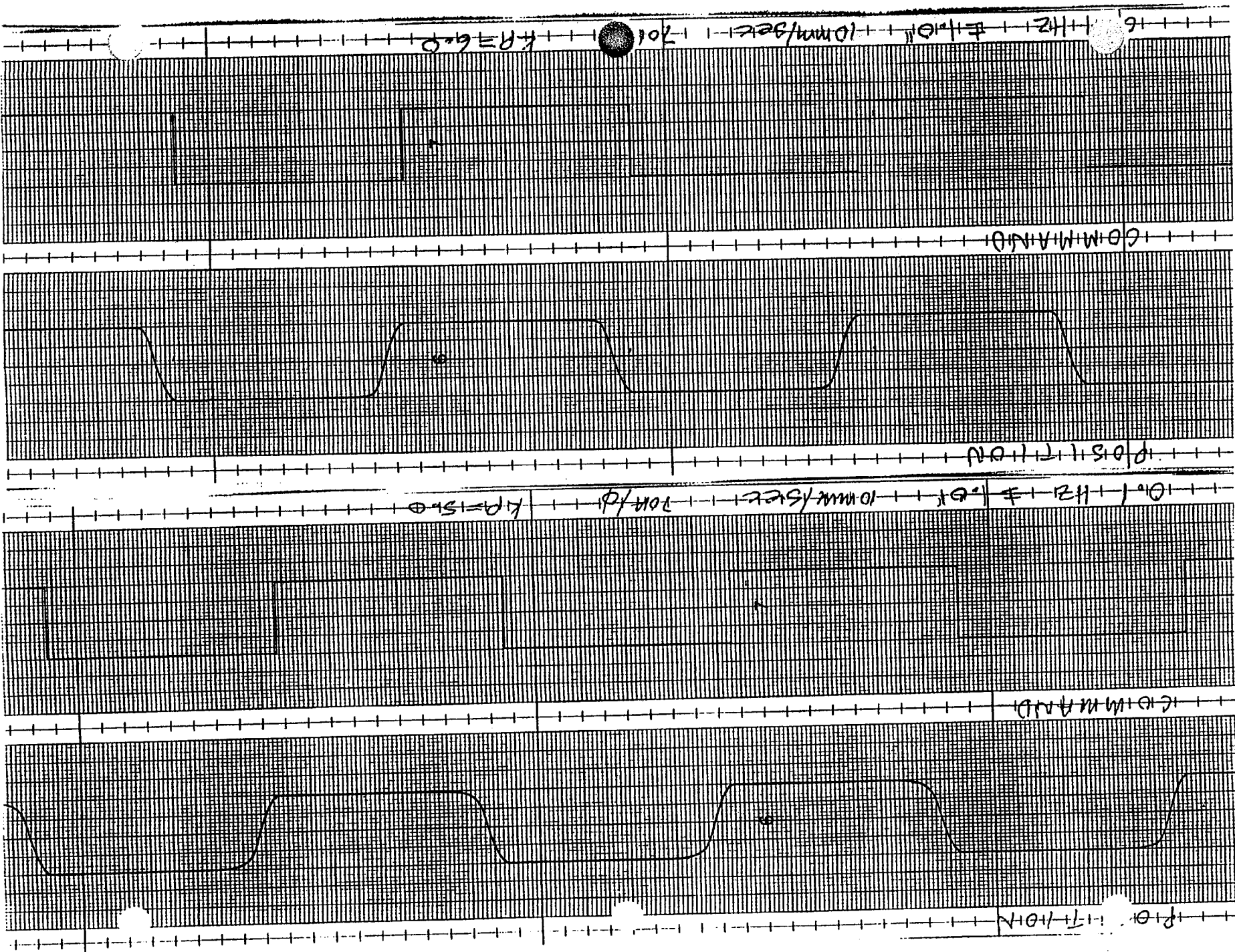


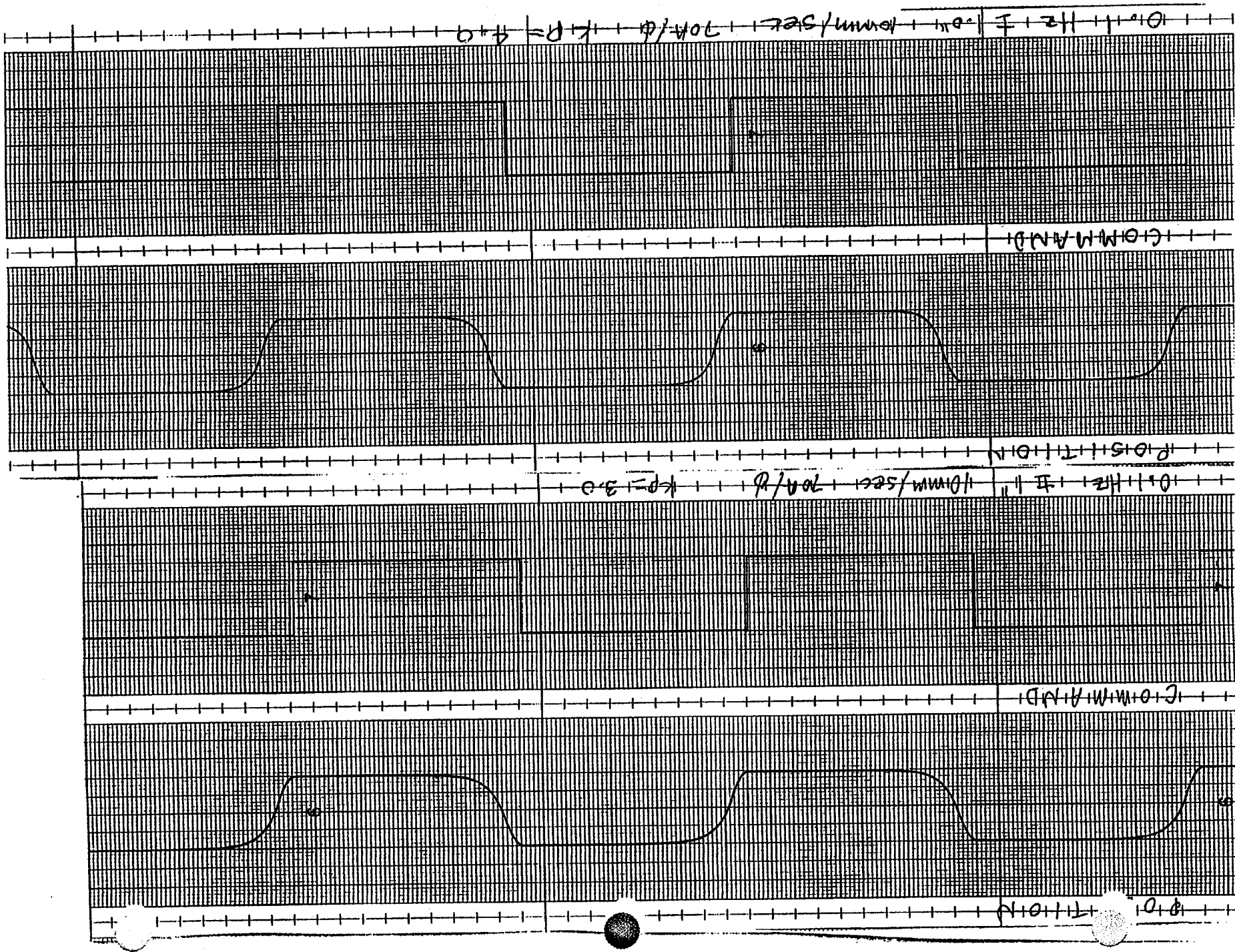




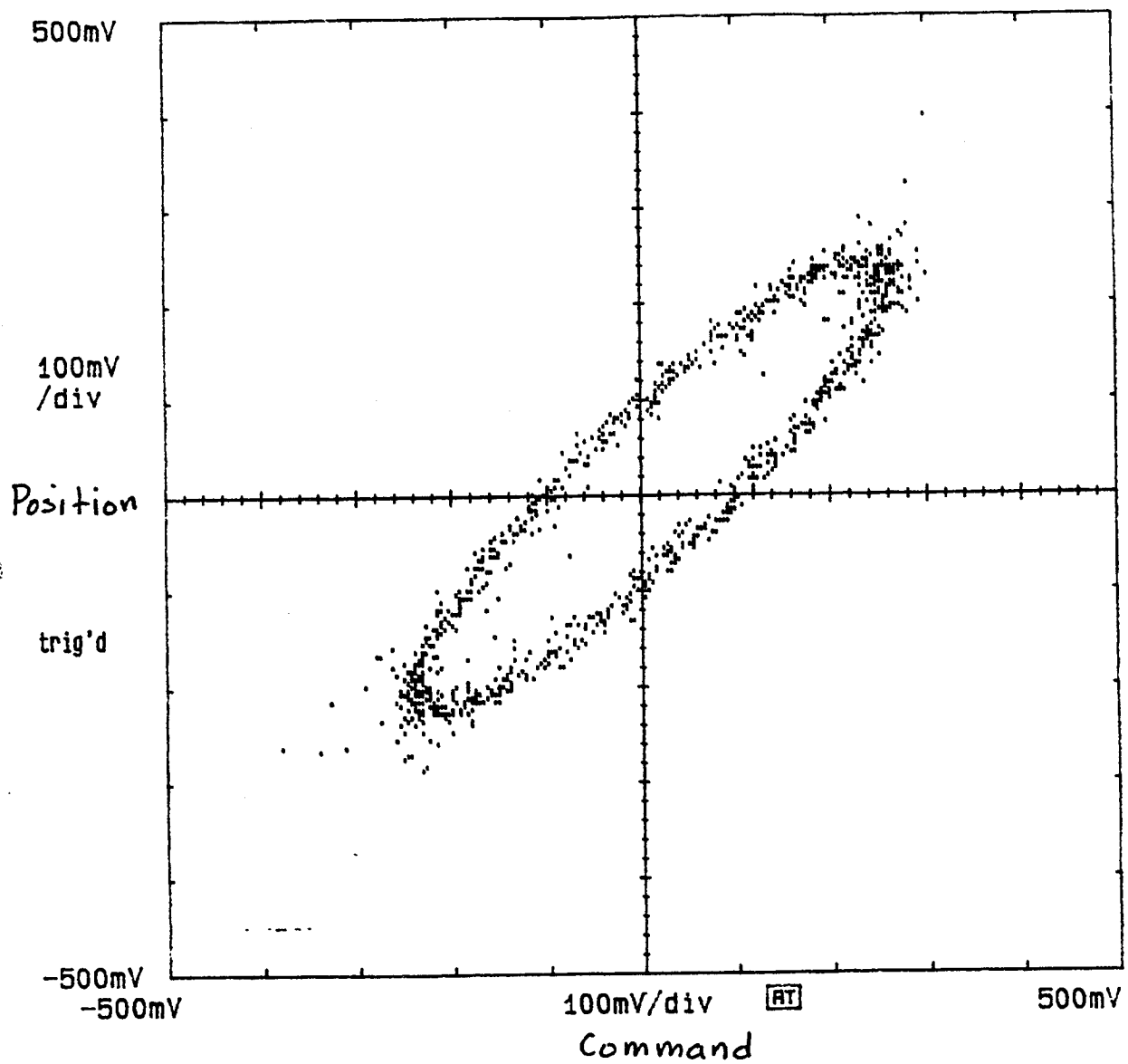








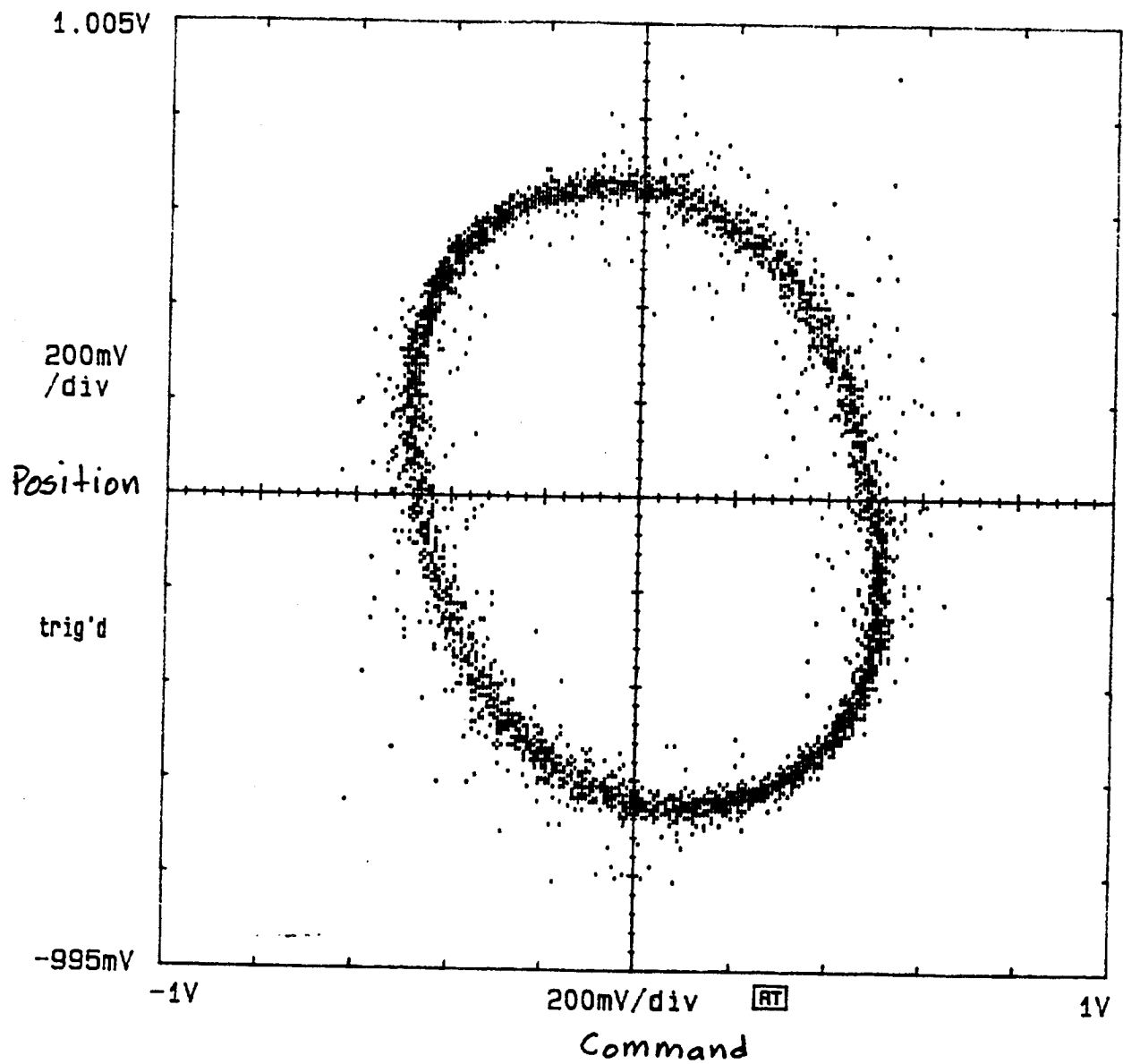
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 23-AUG-93 time: 14:13:53



1.0 Hz \pm 0.25" 70 A/d 12p = 14.3

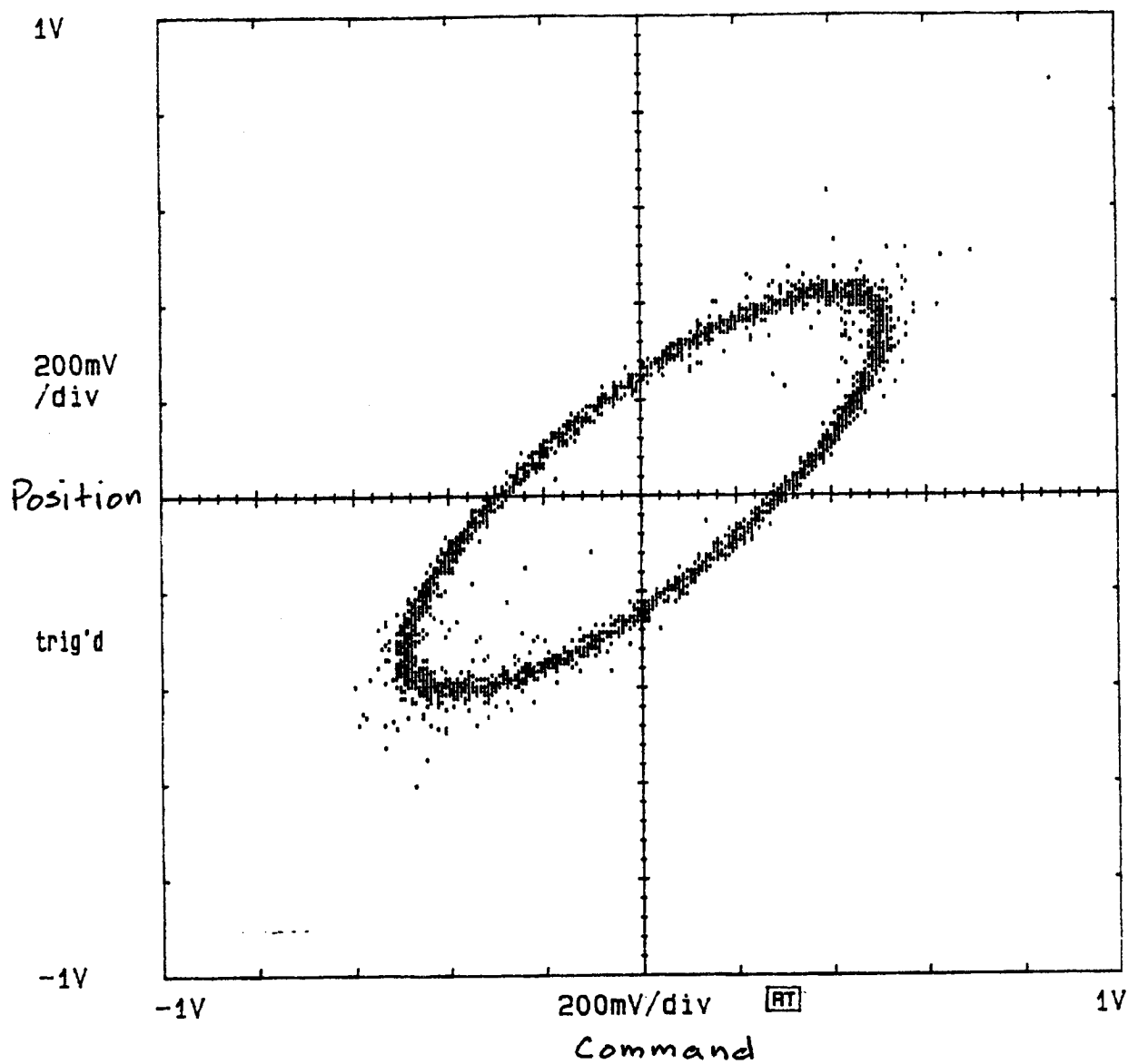
DSA 602 DIGITIZING SIGNAL ANALYZER

date: 23-AUG-93 time: 10:42:24



1.0 Hz $\pm 0.5''$ 70A/φ $K_p = 14.3$

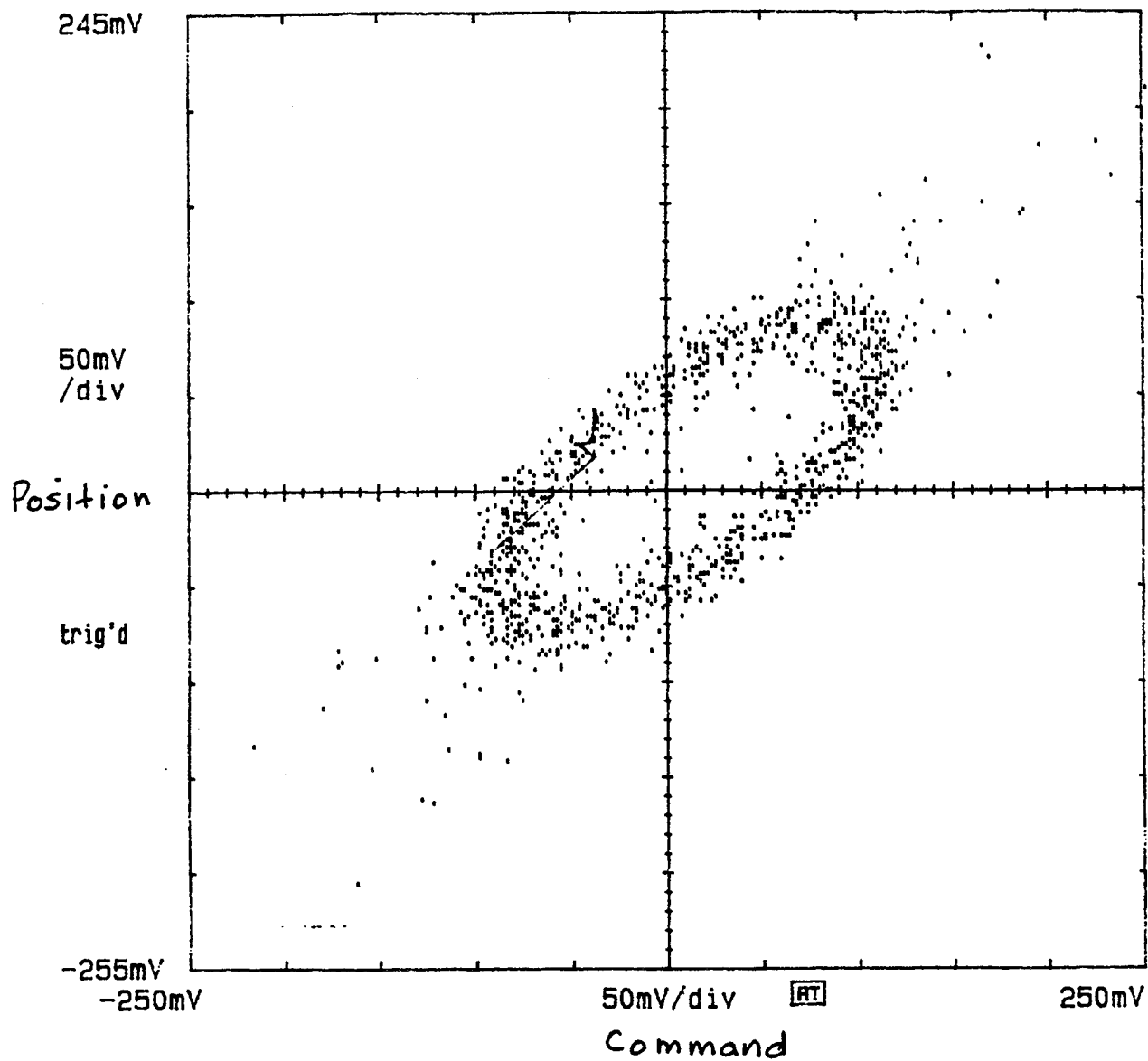
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 23-AUG-93 time: 12:33:48



$1.0147 \pm 0.5''$ $70A/\phi$ $K_p = 9$

DSA 602 DIGITIZING SIGNAL ANALYZER

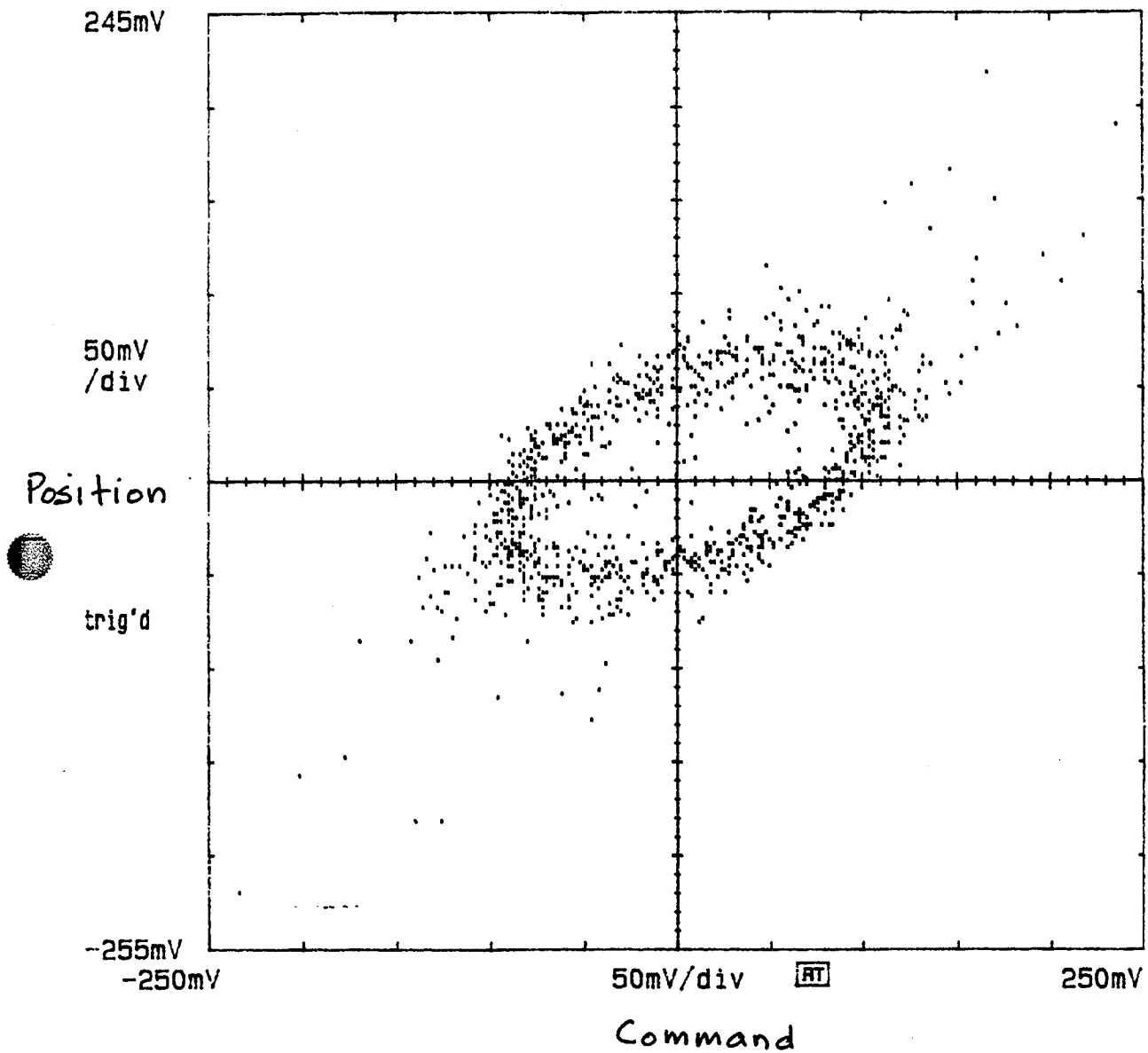
date: 23-AUG-93 time: 13:53:37



$2.0 \text{ Hz} \pm 0.1''$ $70 \text{ A} / \phi$ $k_p = 14.3$

DSA 602 DIGITIZING SIGNAL ANALYZER

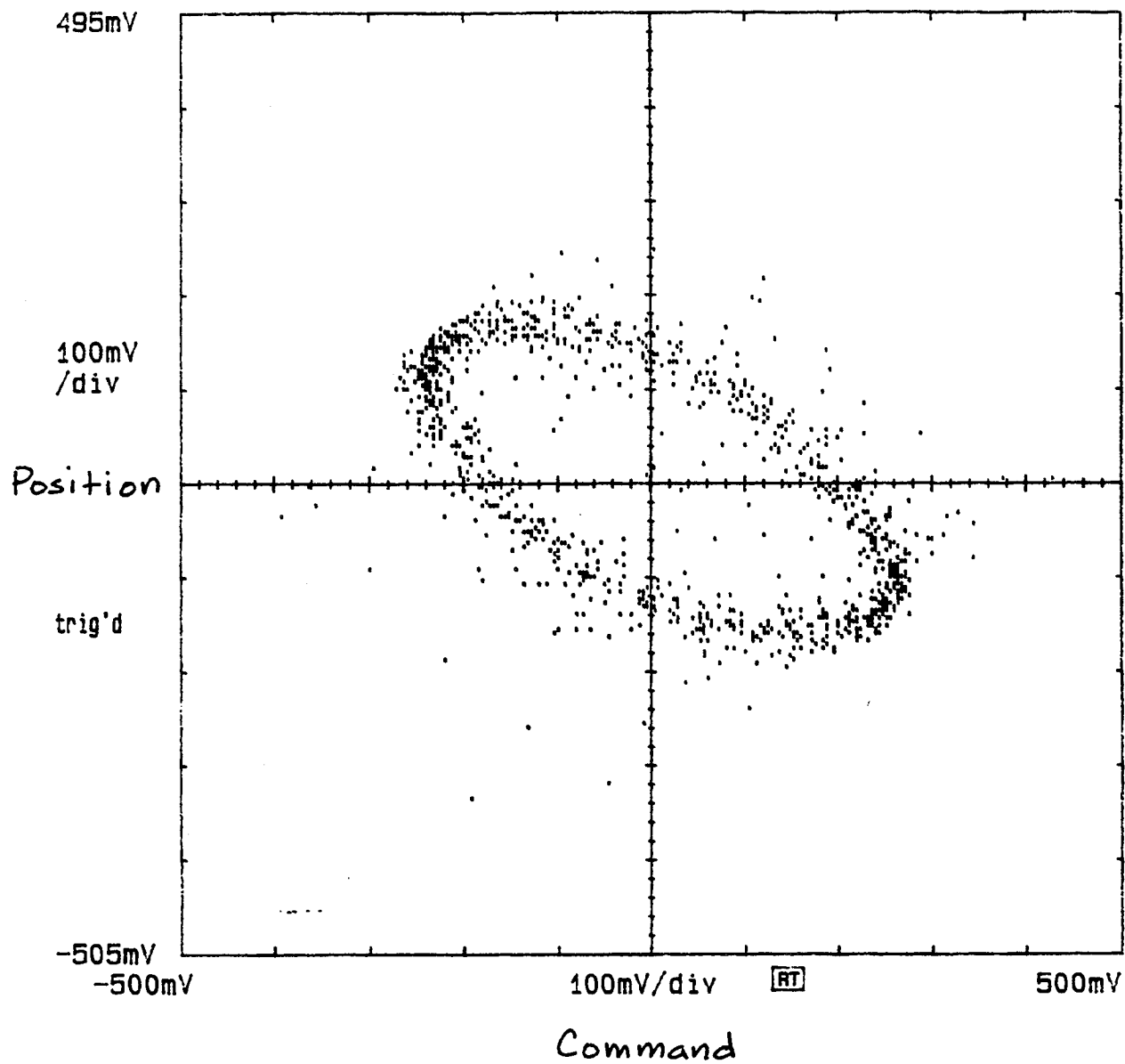
date: 23-AUG-93 time: 14:00:13



2.0 Hz ± 0.1 " 70A/ ϕ $k_p = 9$

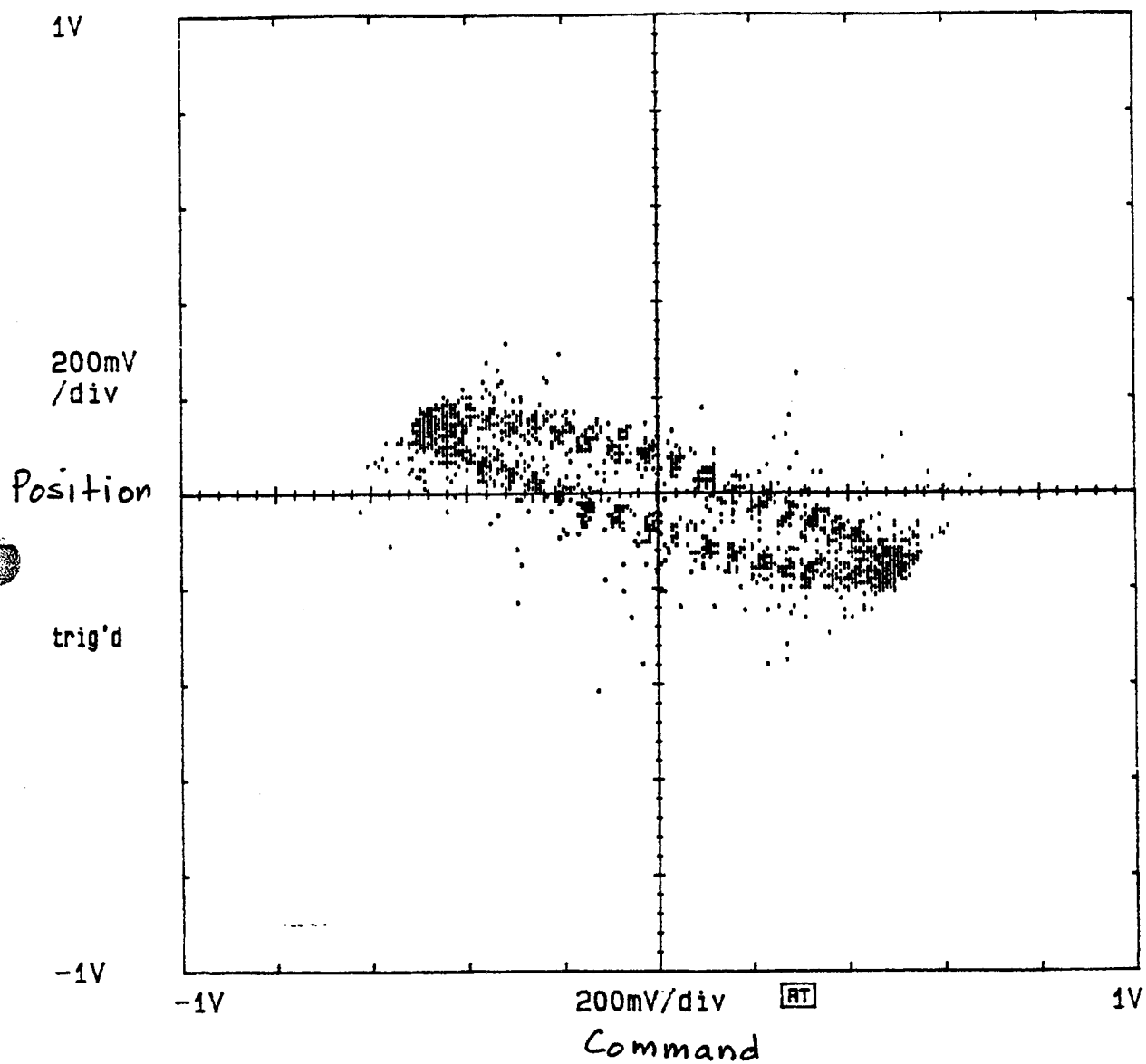
DSA 602 DIGITIZING SIGNAL ANALYZER

date: 23-AUG-93 time: 14:06:46



2.0Hz $\pm 0.25''$ 70A/φ Kp= 14.3

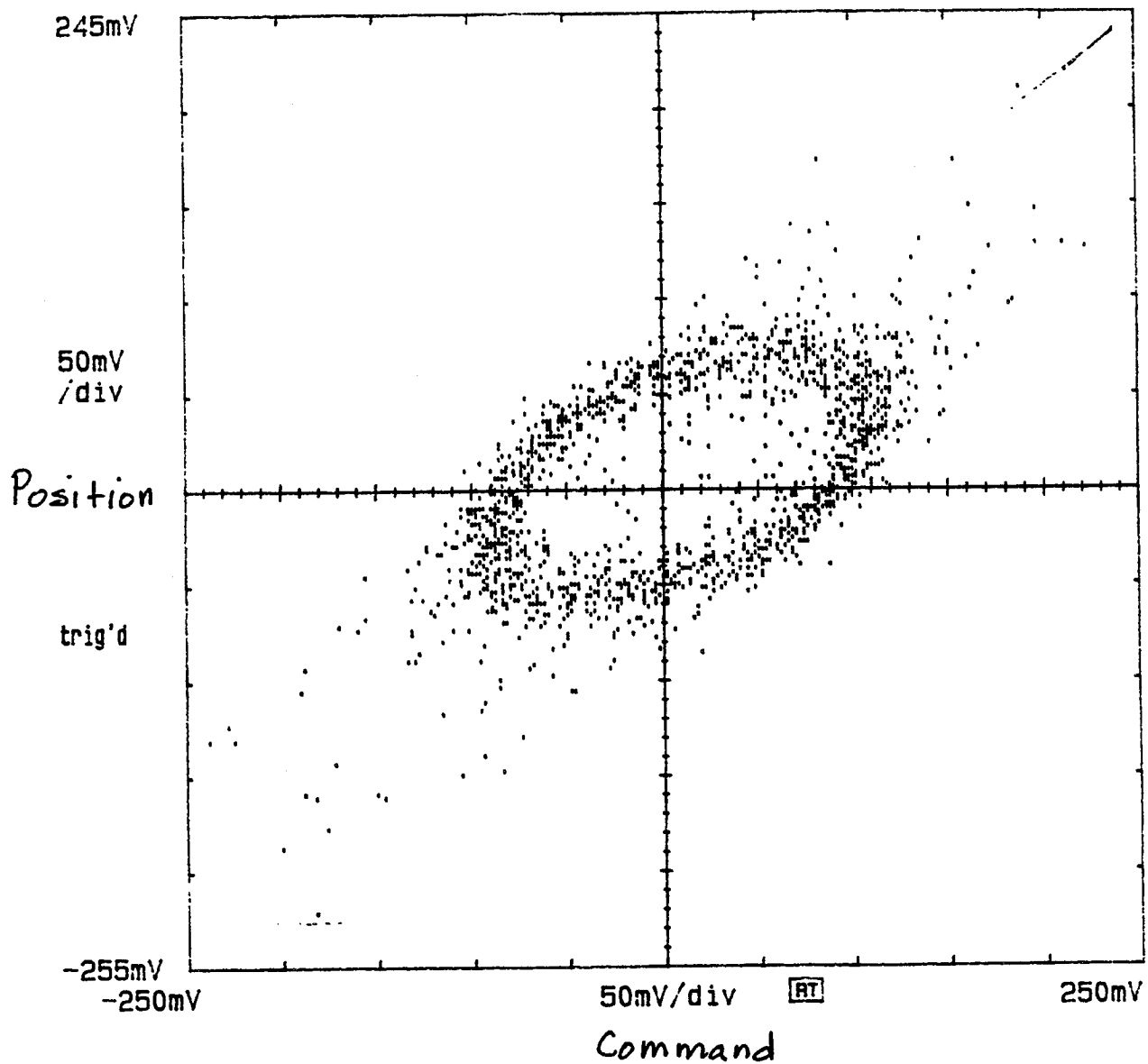
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 23-AUG-93 time: 12:45:12



2.0 Hz $\pm 0.5''$ 704/0 Kp=14.3

DSA 602 DIGITIZING SIGNAL ANALYZER

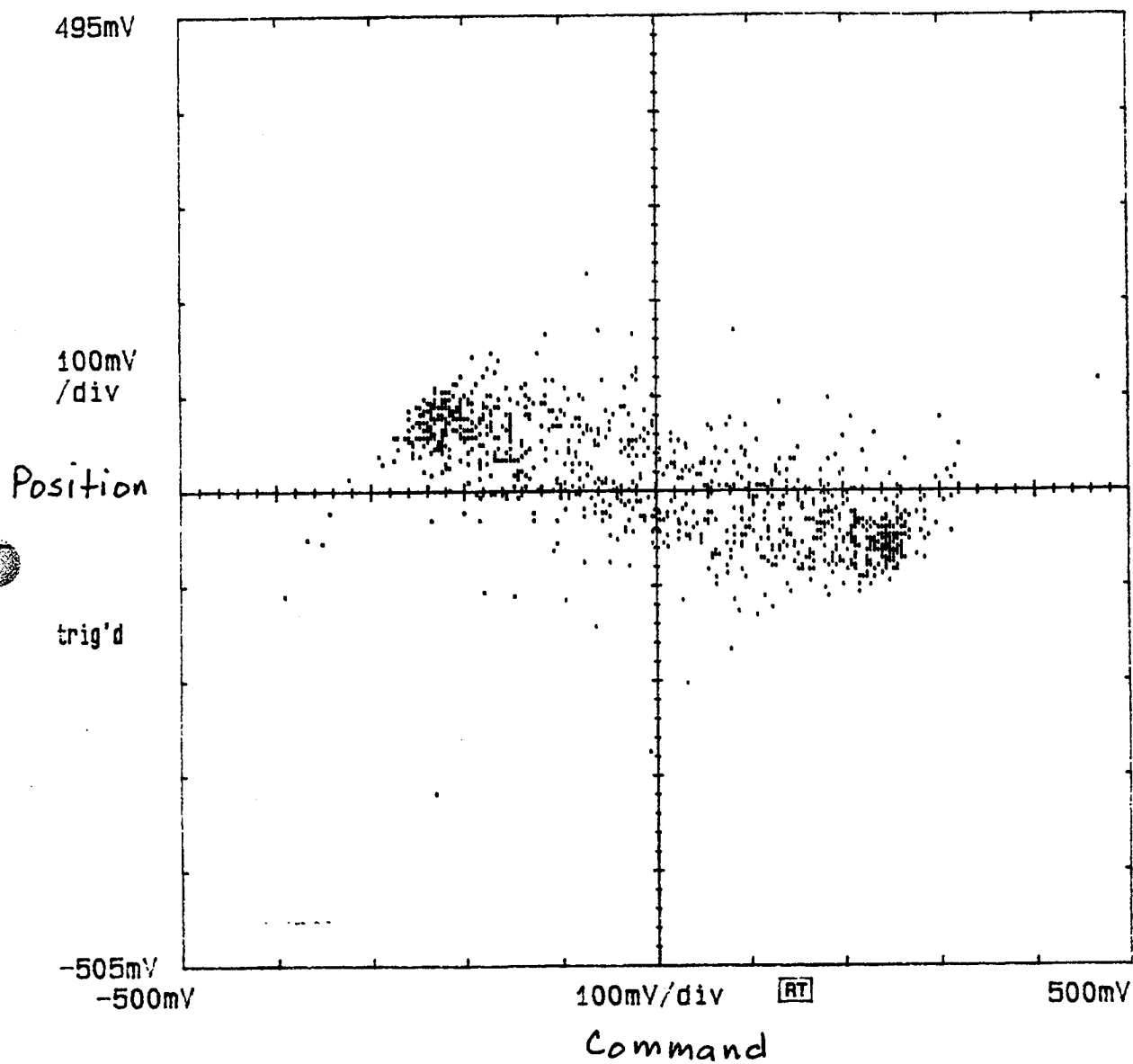
date: 23-AUG-93 time: 13:38:47



$3.0 \text{ Hz} \pm 0.1''$ $70 \text{ A}/\phi$ $K_P = 14.3$

DSA 602 DIGITIZING SIGNAL ANALYZER

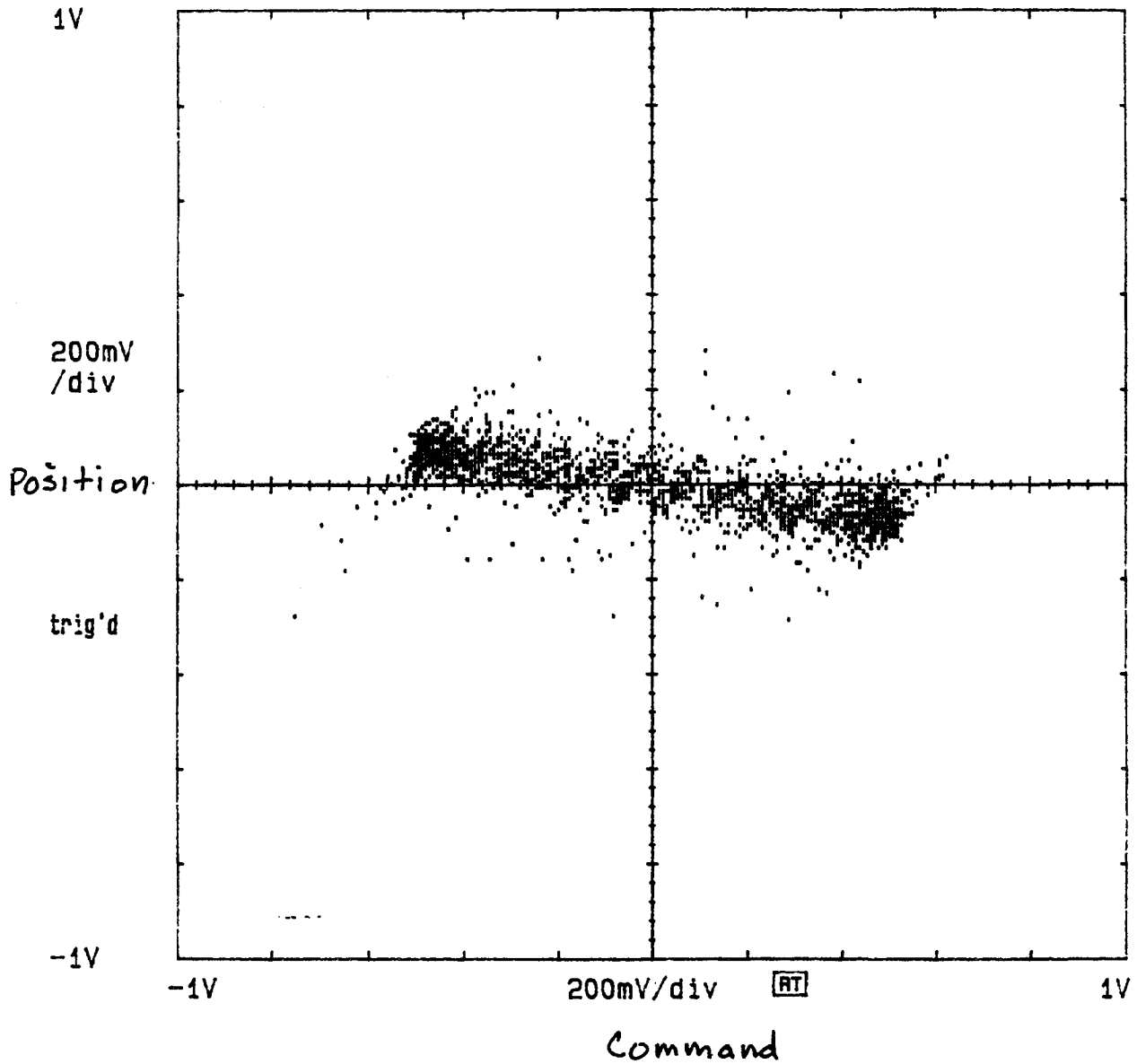
date: 23-AUG-93 time: 13:47:07



3.0 Hz $\pm 0.25''$ 7014 / ϕ KP = 14.3

DSA 602 DIGITIZING SIGNAL ANALYZER

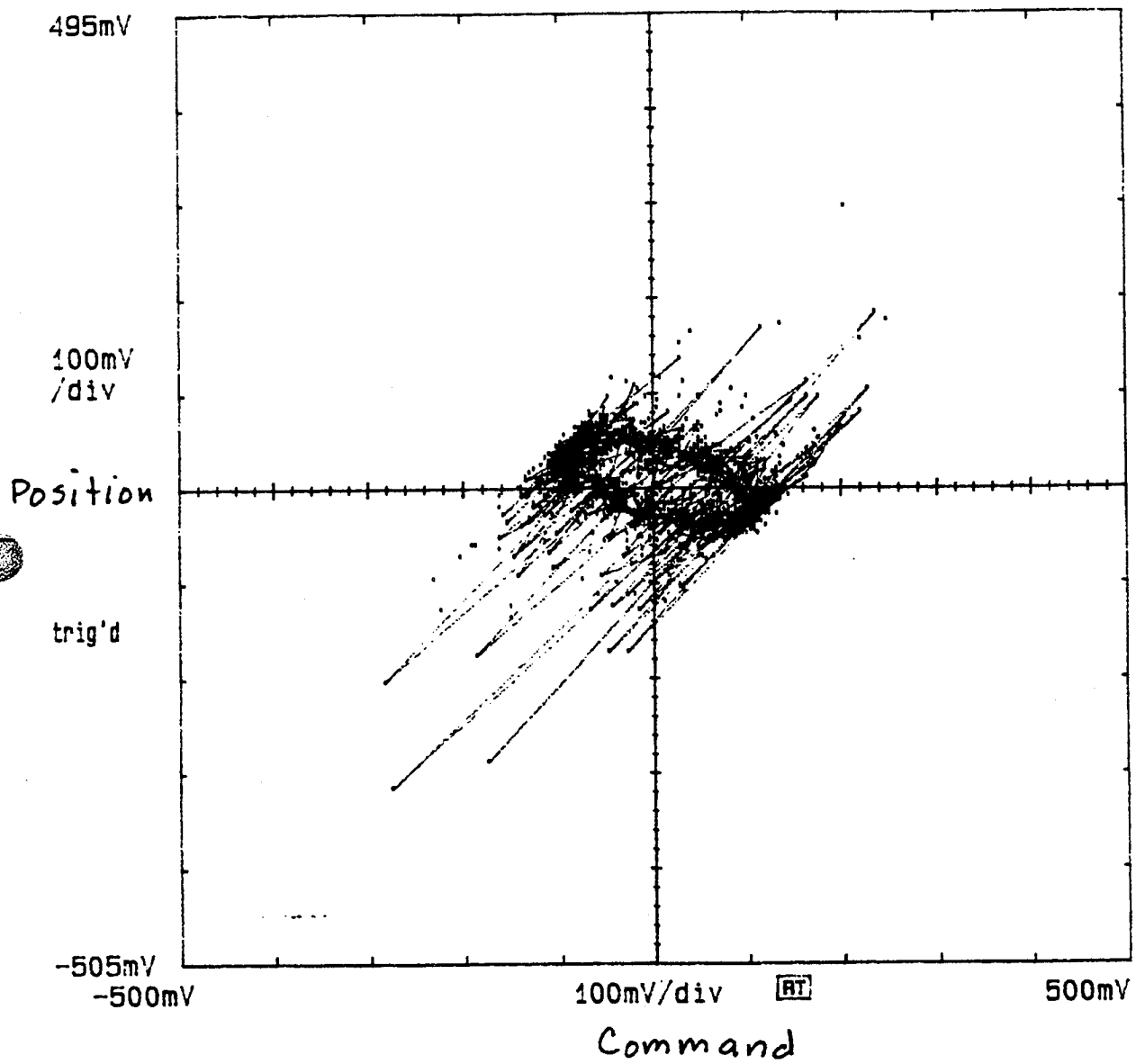
date: 23-AUG-93 time: 12:53:51



$3.0 \text{ Hz} \pm 0.5''$ $70 \mu\text{A}/\phi$ $K_P = 14.3$

DSA 602 DIGITIZING SIGNAL ANALYZER

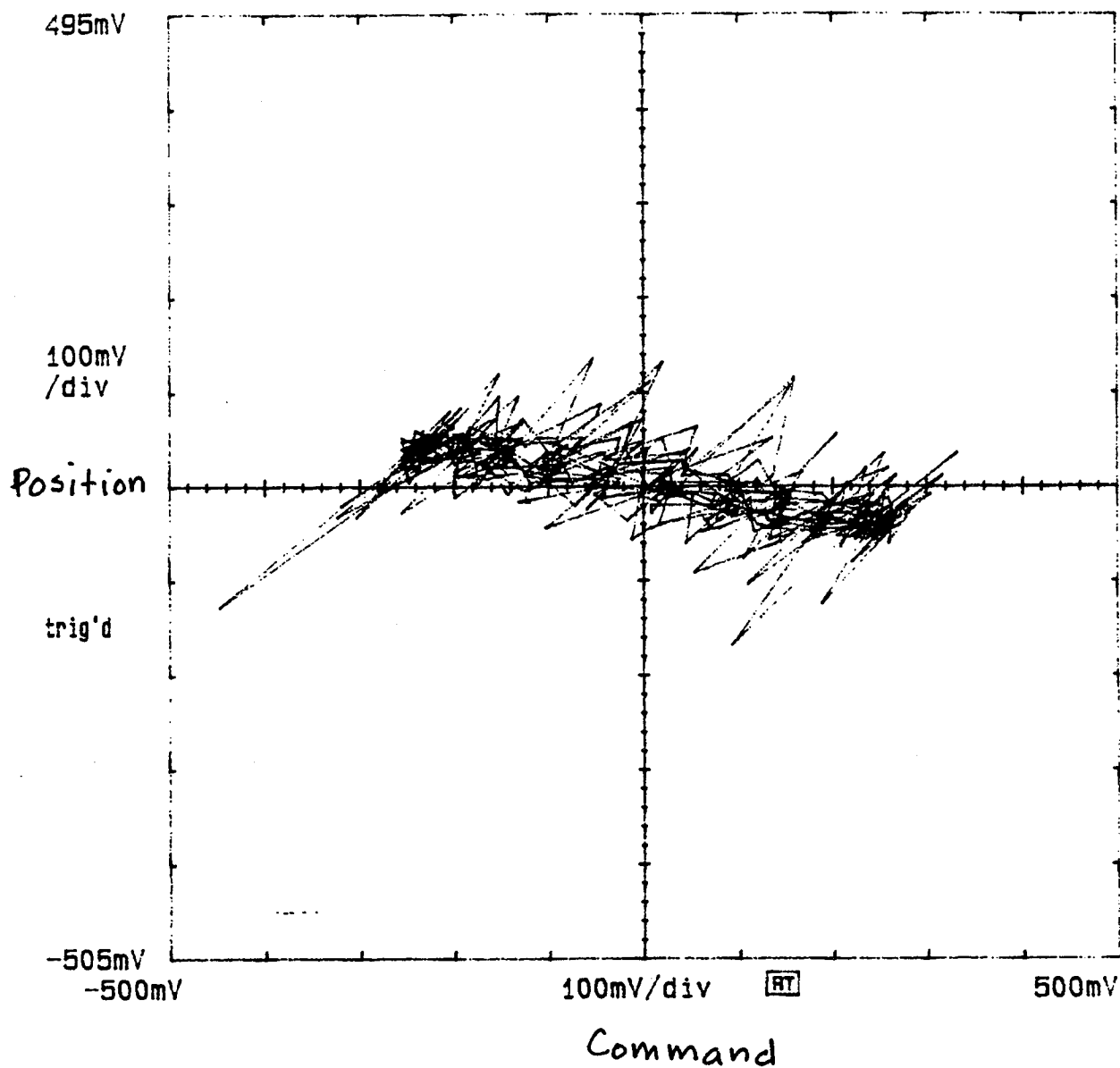
date: 23-AUG-93 time: 13:32:01



4.0 Hz $\pm 0.1''$ 70A/ ϕ $K_P = 14.3$

DSA 602 DIGITIZING SIGNAL ANALYZER

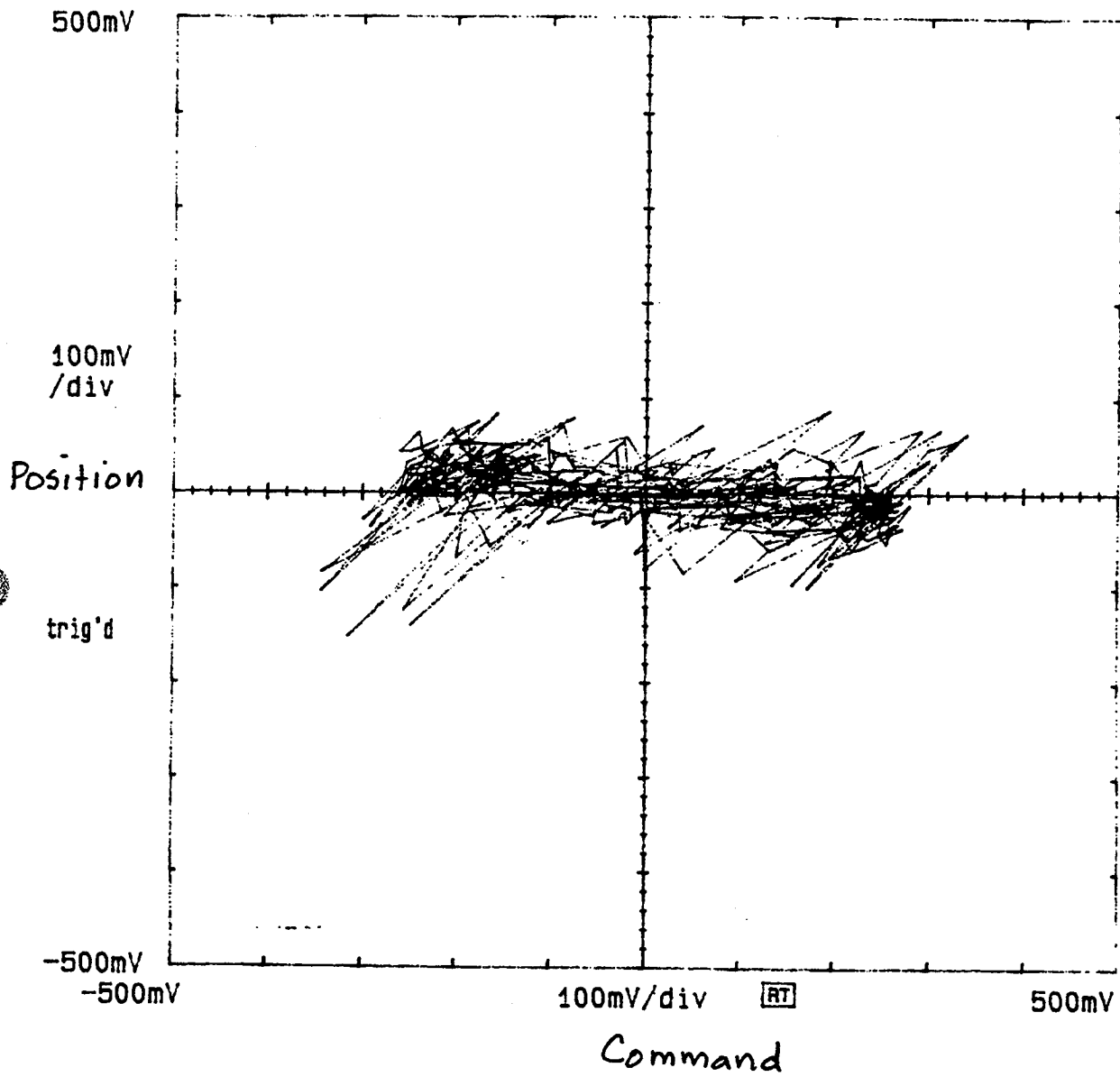
date: 23-AUG-93 time: 13:28:38



4.0 Hz $\pm 0.25''$ 70A/ ϕ $K_p = 14.3$

DSA 602 DIGITIZING SIGNAL ANALYZER

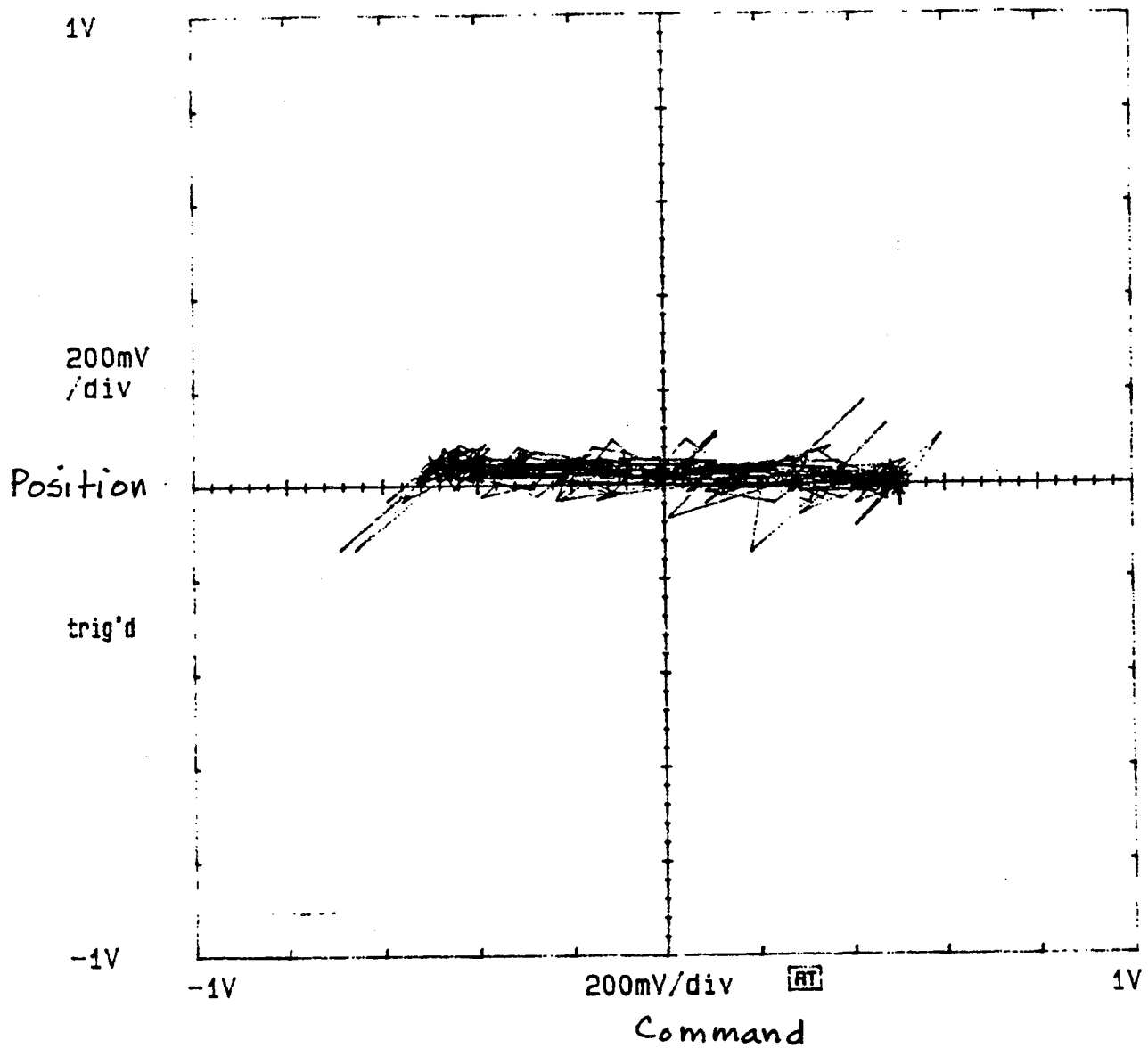
date: 23-AUG-93 time: 13:17:07



6.0 Hz $\pm 0.25^u$ 70A/φ Kp = 14.3

DSA 602 DIGITIZING SIGNAL ANALYZER

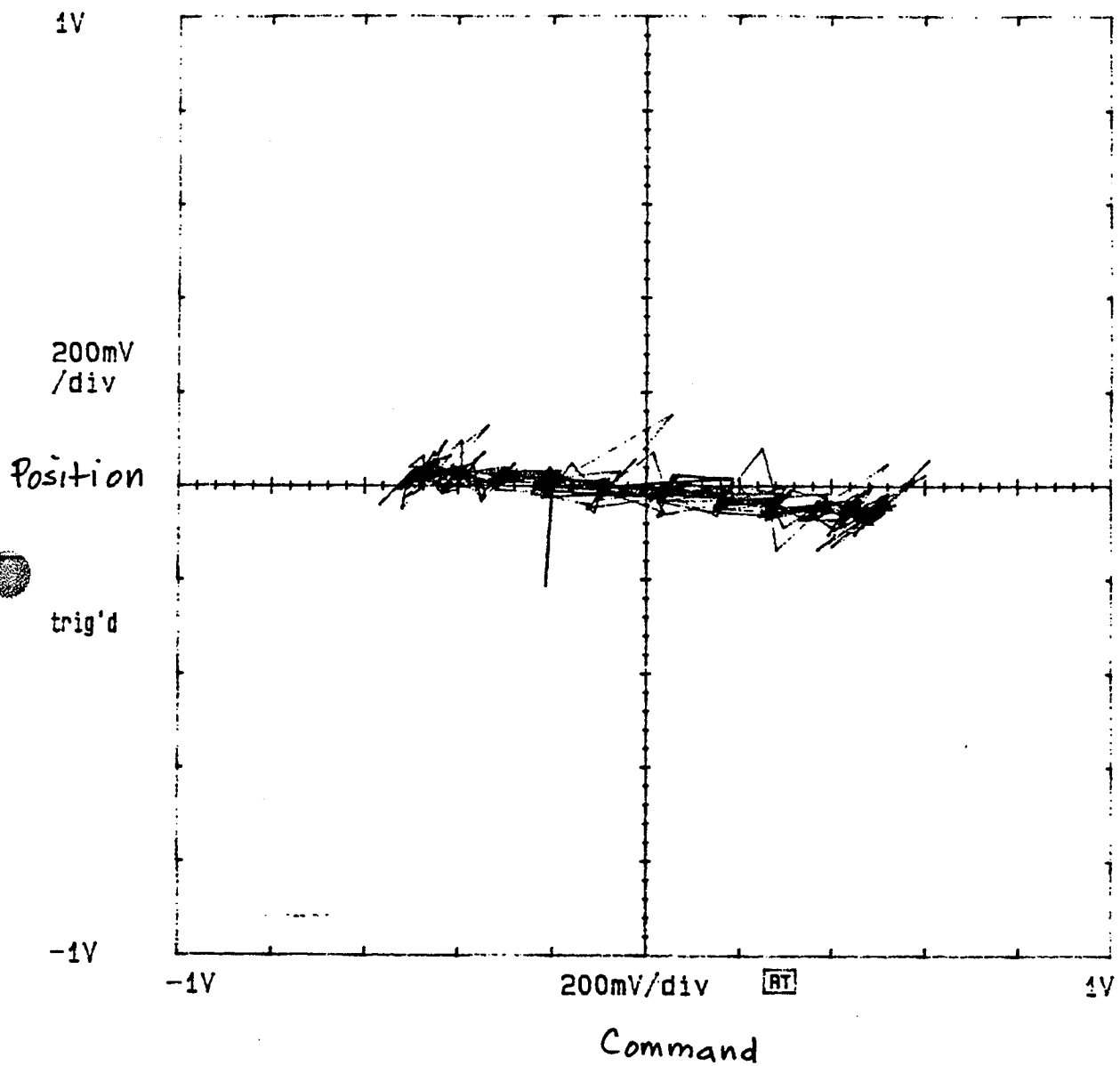
date: 23-AUG-93 time: 13:15:11



6.0 Hz $\pm 0.5^{\mu}$ 70 A/p $R_p = 14.3$

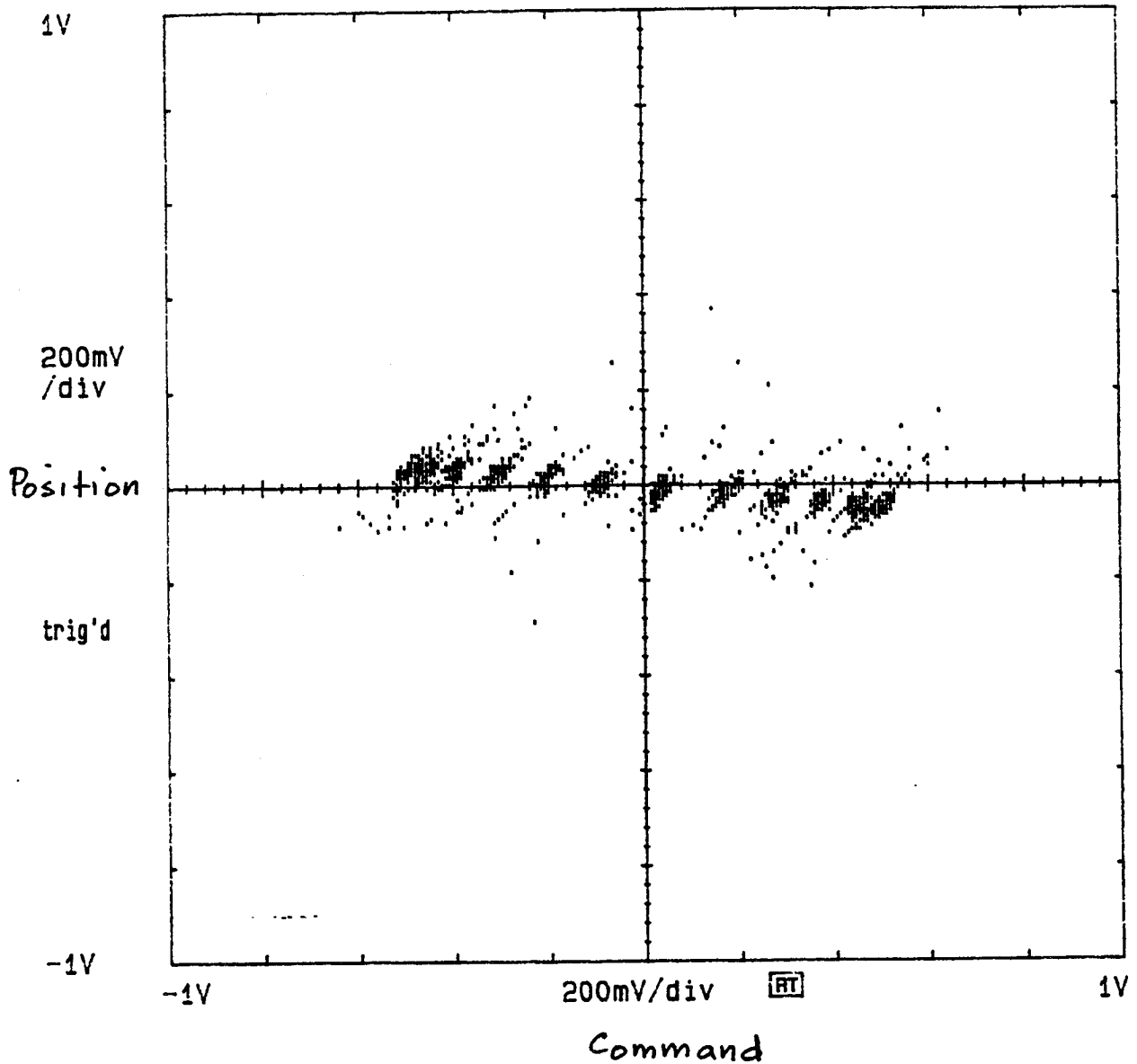
DSA 602 DIGITIZING SIGNAL ANALYZER

date: 23-AUG-93 time: 13:12:55



4.0 Hz $\pm 0.5^\circ$ τ_{OA}/ϕ $K_P = 14.3$

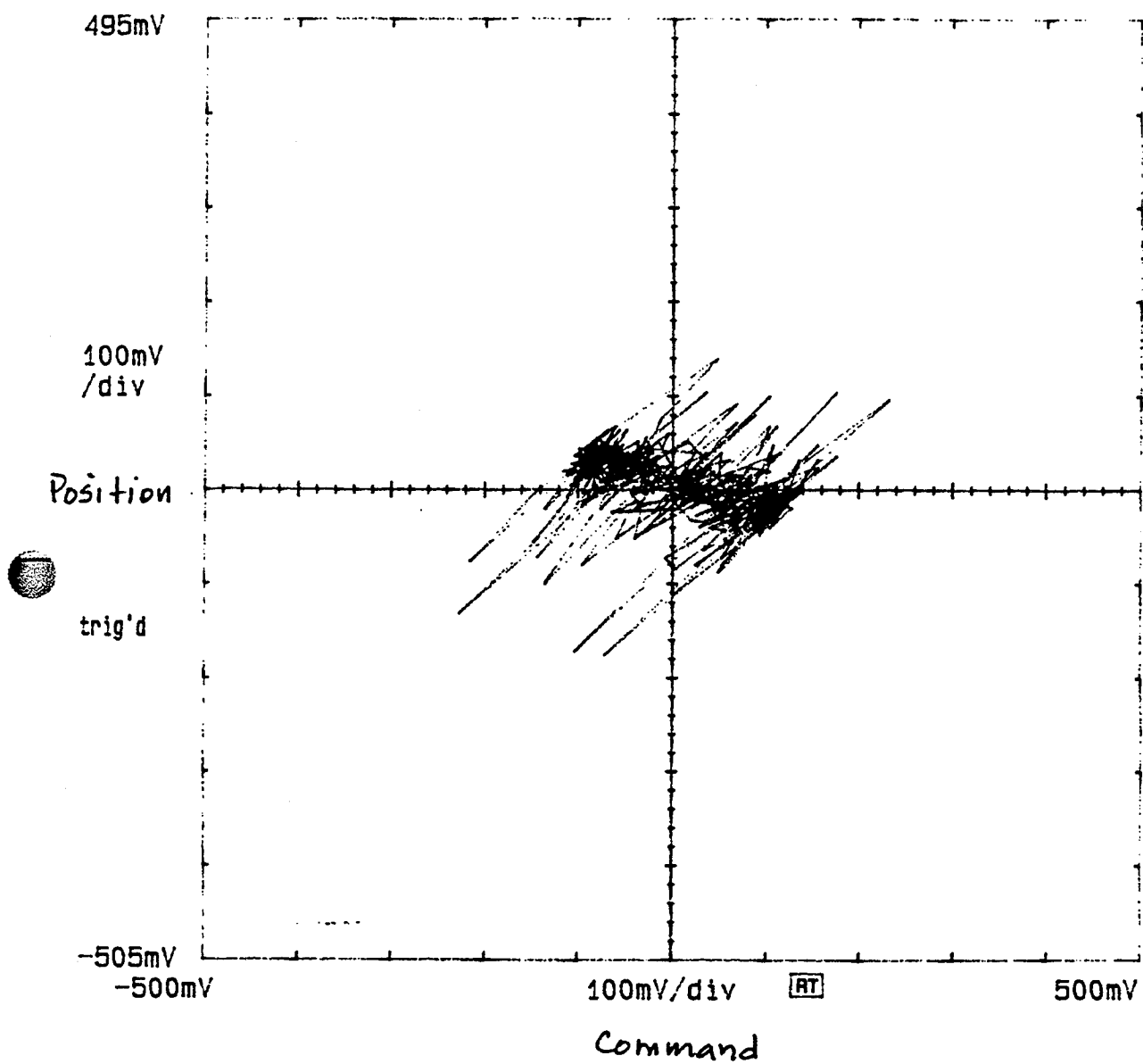
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 23-AUG-93 time: 13:03:54



4.0 Hz \pm 0.5" 70 A/c $k_p = 14.3$

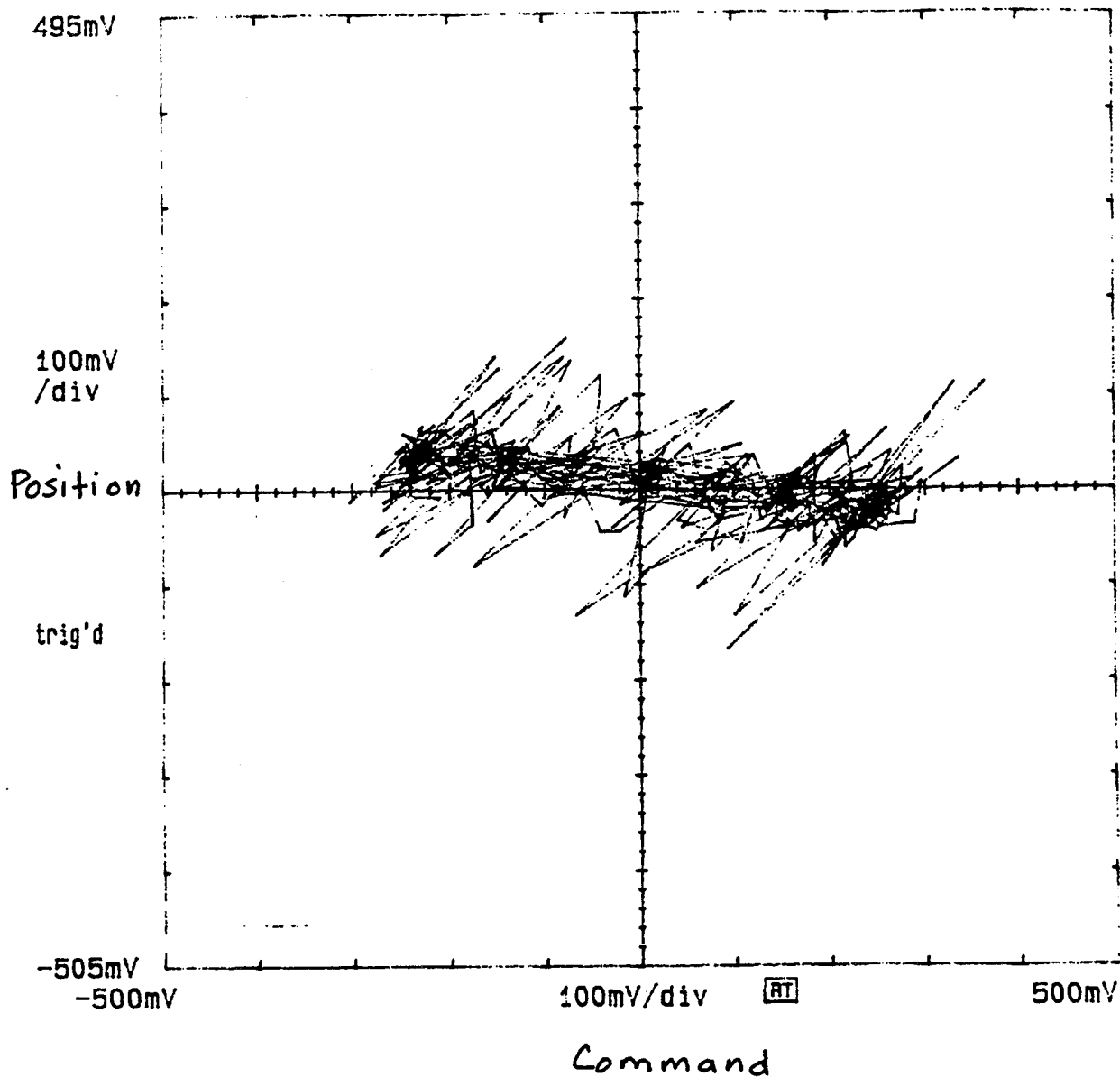
DSA 602 DIGITIZING SIGNAL ANALYZER

date: 23-AUG-93 time: 13:24:15



5.0 Hz ± 0.1 70A/φ Kp=14.3

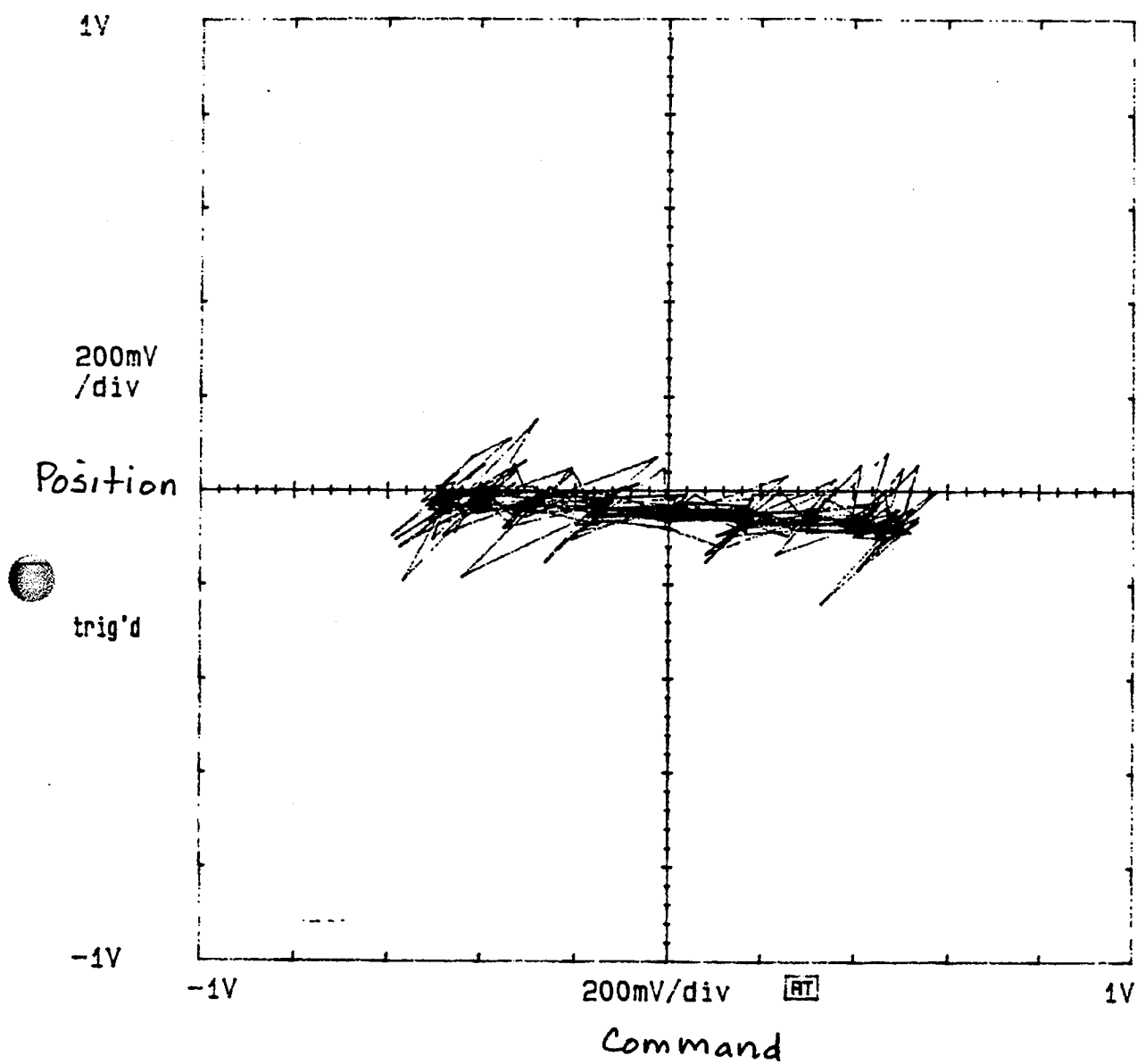
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 23-AUG-93 time: 13:26:37



5.0 Hz $\pm 0.25''$ 70A/6 Kp = 14.3

DSA 602 DIGITIZING SIGNAL ANALYZER

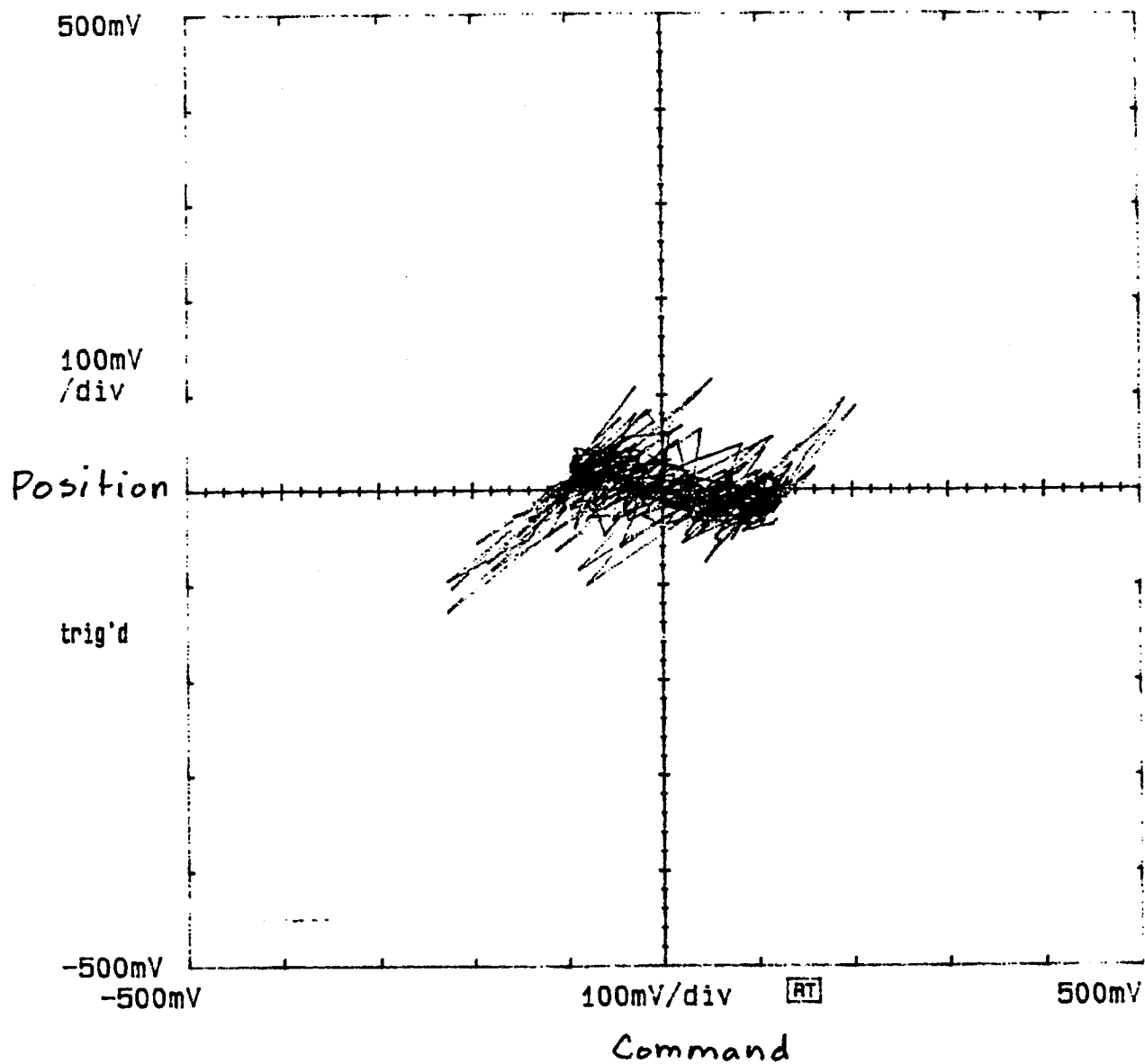
date: 23-AUG-93 time: 13:08:53



5.0 Hz $\pm 0.5''$ 70A/ ϕ Kp = 14.3

DSA 602 DIGITIZING SIGNAL ANALYZER

date: 23-AUG-93 time: 13:19:44



6.0 Hz $\pm 0.1''$

70A/ ϕ

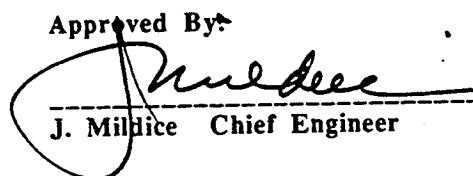
LP=14.3

40 HP Electro-Mechanical Actuator Final Report

Contract: NAS3-25799

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General Dynamics Space Systems
San Diego, CA

Approved By:


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40 HP Electro-Mechanical Actuator Final Report

1. INTRODUCTION

1.1 Scope

This report summarizes the work performed on the 40 HP electro-mechanical actuator (EMA) system developed on NASA contract NAS3-25799. The 40 HP system consists of a motor controller system and a linear actuator capable of up to 50,000 lbs loading. The system is designed to demonstrate the capability of large, high power linear actuators for applications such as Thrust Vector Control (TVC) on rocket engines. This system utilizes a resonant power supply that operates at 20 KHz. The 20 KHz power supplies were developed on the NASA Space Station Program and are used in this system as part of the facilities power source.

This program was started in 1990 with the development and design of the 40 HP motor controller. The system was constructed and tested culminating with a demonstration at NASA Marshall Space Flight Center in September of 1992. The system was modified to improve performance and reliability and retested in 1993. This report is a summary of the work that has been completed on this program.

2. OVERVIEW OF SYSTEM HARDWARE AND SOFTWARE

2.1 System Hardware

The system hardware consists of a linear actuator with an induction motor, a motor controller power stage, a motor controller card cage, a terminal & keyboard and a low voltage power supply. Refer to Appendix A for pictures of these items. Refer to the Hardware Documentation Package for a complete guide to the hardware including schematics.

2.1.1 Actuator

The actuator was designed and built by Moog Aerospace to meet or exceed the Space Shuttle Main Engine Thrust Vector Control (TVC) requirements. The actuator converts the rotary motion of the induction motor to linear motion and is capable of up to 48,000 lbs. of stall loading. Impulse loads of up to 100,000 lbs will not damage the unit. The 14,700 RPM top speed of the motor translates to 5.2 inches per second of linear motion. The range of motion is ± 5.5 inches with a rated acceleration of 60 in/sec/sec. An LVDT (Linear Variable Displacement Transducer) is used to measure the linear motion of the actuator. The LVDT

is mounted in the housing of the actuator and is connected to the motor controller by a dual twisted pair cable with connectors on each end. The LVDT accepts a sinusoidal reference signal and returns a sinusoidal drive signal that varies in phase and amplitude, dependent on the linear position of the actuator. These signals are processed by the motor controller electronics.

2.1.2 Motor

The motor is a Sundstrand designed, AC Induction motor capable of 35 continuous HP and 70 peak HP. It was designed to provide a high power to weight ratio and attains about 3.5 peak HP per pound with a weight of 19.6 lbs. The motor is a six pole, 3 phase design with a top speed of 14,700 RPM. Cooling is achieved by conduction through the motor bearings and housing to the actuator body. The motor is designed to require no additional cooling when operating in its TVC environment for a typical 10 minute mission. Forced air cooling may be used during extended laboratory testing by connecting two air fittings located on the top of the motor to filtered shop air. The motor's magnetics are constructed from Hyperco-50. A Harowe resolver (#21BRCX-335-512) is mounted on the motor to provide motor position and speed information. The resolver is a six terminal device with 2 reference frequency input lines and 2 cosine and 2 sine output lines. The angular position of the rotor is determined by comparing the input reference with the output signals. There is also a thermocouple embedded in the motor's stator which may be used to measure motor temperature. The rotor's temperature may be measured through an access hole located on the motor's rear housing. A full continuous power output of 35 HP is specified with an input current of 106 A/phase. The peak power output of 70 HP is predicted with an input current of 210 A/phase.

2.1.3 Motor Controller Card Cage

The motor controller card cage was designed, fabricated and tested at General Dynamics Space System Division. The motor controller card cage contains four cards mounted to a VME backplane.

The first card is a **Motorola 68030 single board computer**. The computer controls all aspects of the system's operation. Operating data may be entered into this system computer by using the terminal monitor and keyboard. The computer is connected to the terminal monitor via an RS-232 interface. The computer communicates to the other cards in the motor controller card cage over a 16 bit VME data bus.

The second card is the **input/output board** and it performs I/O functions. It contains one A/D converter and two D/A converters. The A/D converter is used as the external signal input to drive the actuator. The input voltage range is ± 10 VAC. This A/D only functions if selected as an input on the terminal monitor screen (see section 3.2.2; waveform=3). The two D/A converters are used as instrumentation outputs with a voltage range of ± 10 volts. D/A converter #1 outputs the commanded actuator position signal. The user may select the signal output on D/A converter #2 from a choice of 36 signals. A detailed explanation of these signal choices is given in section 3.2.1.1.

The third card is the **VME interface** card. This card interfaces the single board computer to the rest of the controller's hardware. There are several functions performed by the interface card including bus interface operations, D/A conversions, programmable timer operations, resolver to digital conversion and LVDT to digital conversion.

The fourth card is the **modulator** which performs analog motor control functions, motor current regulation and power switch sequencing/timing. Two motor control functions performed by this card are sine and cosine reference signal generation, and a 2 phase to 3 phase conversion required by the field oriented control method. The motor current regulation is accomplished by comparing the 3 phase motor current reference signals to the current feedback from motor phases A and B. Actual phase C motor current is calculated as the sum (or difference) of motor phase A and B currents. The power switch sequencing circuit evaluates which state the power stage switches should go to next, to achieve regulation of the motor's current. This function is performed in two stages, first by an EPROM, then a set of PLD's. The EPROM looks at the previous switch states and the current error signals from the current regulator and determines the best switch state to correct the current error, for each phase. The output of the state selector goes to a switch sequencing set of PLD,s (ATV750's). These devices generate switch timing signals that are in synchronization with the zero crossings of the 20 KHz link and have the proper delays to allow the power stage transistors to switch correctly. The outputs from the power switch sequencing circuit exit the motor controller card cage via a harness and connect to the power stage box.

2.1.4 Motor Controller Power Stage

The motor controller power stage houses the resonant tank circuitry as well as the power switches and associated drive circuitry. The tank circuit is a parallel resonant tank comprised of a 3.4 uF capacitive bank and a 18.4 uH choke. There are 12 power switches which are IGBT's (insulated gate bipolar transistors) rated at 150 amps and 1200 volts. They are packaged in 7 dual transistor "blocks" that bolts down to the power stage bottom plate. The drive boards have optically coupled inputs, and an individual power supply for each of the 12 drive channels. The driver boards require a +5V and an isolated +15V supply. There are two motor current sensors that are mounted to the power stage bottom plate. These sensors require ± 15 VDC and are used to measure the motor's phase current. This information is used by the current regulator circuitry on the modulator board. The power stage switches 350 VAC at 20 KHz, to produce 208 VAC from phase to phase, at up to 90 RMS amp/phase.

2.1.5 Low Voltage Power Supply

A low voltage power supply is housed in a separate box and is used for powering the motor controller card cage circuitry, the motor controller power stage's driver circuitry and the current sensors. The power supply requires 120 VAC input for operation. There is a power on/off switch on the back of the unit, and a voltage indicator on the front of the unit. The rotary switch adjacent to the voltage indicator may be used to select different internal voltage test points. The power supply has 6 output voltages; ± 12 VDC, ± 15 VDC +5 VDC and +15 VDC isolated (for use by the driver boards in the power stage). The +15

VDC isolated cannot be measured on the voltage indicator. It is important that the low voltage power supply be turned on first when operating the unit.

2.2 System Software

The system software is programmed into 2 EPROM's that are resident on the single board computer in the motor controller card cage. It controls all aspects of the system's operation. The monitor keyboard input/output functions are controlled by the software. The software also performs all of the algorithms that control the actuators position, and speed. The system software is comprised of three separate types of code. The operating system (PSOS+) is a purchased product, configured to work on this 68030 based system. Portions of the lower level input/output code, user interface software and device interface code are hand coded in the "C" programming language. The higher level control algorithms were designed using the Matrix_x development environment. This is a rapid prototype and development environment which allows the system software to be designed using block diagrams. After simulations and verifications, the block diagrams are auto-coded into the "C" programming language. Subsequent changes are greatly simplified because of the block diagram format and auto-coding features. Refer to the "Electromechanical Actuator 40 HP Motor Controller Software" Documentation Package for a complete guide to the software.

3. SYSTEM OPERATION

3.1 Powering On

The system must be energized in two steps:

1) Low Voltage Operation On

The low voltage power supply runs the single board computer and the control electronics. It must be turned on first so that the operator has control of the system via the terminal keyboard. The single board computer performs a self-test when first energized. This verifies the operation of the computer board and the VME interface connecting to the adjacent modulator, I/O and interface cards. The low voltage power is also distributed to the driver cards and current sensors in the output stage electronics. The terminal monitor values must be set appropriately for the operator's desired functions prior to turning on the 20 KHz AC.

2) 20 KHz AC Power On

The 20 KHz AC power should only be applied to the power stage after the operation of the unit has been defined on the terminal monitor. The operating voltage of the power stage is 350 to 380 VAC RMS. It is critical that the commanded currents (I_{qs}^* , I_{ds}^*) are adjusted to their default values upon power up. This is important because the 20 KHz link voltage is unstable at low voltages, when currents are commanded. The 20 KHz link voltage may be applied slowly or switched on to it's rated value.

3.2 Motor Control Panel

The operational information for the EMA system is entered into the single board computer via the terminal monitor keyboard. The EMA Motor Control Panel is the screen which shows up on the terminal monitor. This screen has two distinct sections to it. The Input Variables are listed on the left side of the screen and the Output Variables are listed on the right side of the screen. The following is a table of the input and output variables seen on the terminal screen.

Electromechanical Actuator -- Motor Control Panel

<u>Variable</u>	<u>Value</u>	<u>Units</u>	<u>Variable</u>	<u>Value</u>	<u>Units</u>
Mode Select	0	Ps/Rt/Op	Time	0.00	sec
Waveform	1	Sn/Sq/D/X			
Cmd Ampl	0	In (RPM)	Act Pos	-----	In
Cmd Freq	0	Hz	Act Rate	-----	In/Sec
Ids	0.1	A	Motor Rate	-----	RPM
Iqs Limit	0	A	Cmd	-----	In/RPM
KpLim (Rate)	20	A			
Slip Gain	0.07		Iqs Cmd	-----	Amps
Kp (pos)	14.3		Slip	-----	Hz
Ki (pos)	0				
Kp (rate)	1.53		DA2 Output	-----	Volts
Cmd Bias	0	In (RPM)	Cycle Use	-----	Available
DA1 Gain	1		Frame Use	-----	% avail
DA1 Bias	0				
DA2 Select	6				
DA2 Gain	0.02				
DA2 Bias	0				

Table 3.1

3.2.1 Input Variable Description

Mode Select	Select actuator loop mode: Position = 0 , Rate = 1, Open loop = 2
Waveform	Sinewave = 0, Squarewave = 1 , Demo = 2, External Input = 3
Cmd Ampl	Actuator Excursion $\pm 5.5''$ max. In rate mode 1 inch = 3000 RPM; 0.0 in
Cmd Freq	The commanded frequency of actuator movement; 0.0 Hz
Ids	The commanded value of the flux current; Range is 0 to 90 A; 0.1 A
Iqs Limit	The torque current limit value. Range is 0 to 90 A; 0 A
KpLim (Rate)	The max Iqs current increase allowed by the Kp loop (0 to 90 A); 20 A.
Slip Gain	The slip gain factor used in field oriented control calculations; 0.07
Kp (pos)	The proportional constant for the position loop; 14.3
Ki (pos)	The integral constant for the position loop; 0.0
Kp (rate)	The proportional constant for the rate loop; 1.53
Cmd Bias	The bias (offset) for the zero position on the actuator; 0.0
DA1 Gain	The gain of D to A converter #1. Output = command function; 1.0
DA1 Bias	The bias (offset) value for the output of D to A converter #1 in volts; 0
DA2 Select	Selects the signal to be outputted on D to A converter #2; 6
DA2 Gain	The gain of D to A converter #2; 0.02
DA2 Bias	The bias (offset) value for the output of D to A converter #2 in volts; 0

Bold type indicates the default values.

3.2.1.1 DA2 Select Options

The user may select one of 36 signals as an output of DA2. This enables the user to verify operation of the controller and provides a means to output performance data for use during system testing. The DA2 select defaults on start up to option number 6, which is the digitally derived rate of the motor's speed. Other options may be selected by entering the option number in the DA2 select input field on the terminal monitor. The output signals on DA2 are represented by a voltage that defaults to one volt per unit of measure. For example if option

#12 is selected (slip gain) and its value is 0.1 the output voltage from the D/A converter will be +0.1 volts with DA2 gain = 1. This output value may be scaled by changing the DA2 gain input on the monitor screen. With DA2 gain reset to 20 for instance, the D/A converter output would increase to +2 volts.

Option #	Signal Description
1	Fs Adj -- Slip frequency Adjustment value from controller software.
2	Motor Flux Volts -- The value of the commanded motor flux in volts.
3	Ws -- Omega slip; The slip value.
4	Iqs* -- The commanded torque current
5	Motor Flux -- The value of the motor flux.
6	Digitally Derived Rate in rad per sec -- The motor's rotational speed.
7	Rate Error -- The error present in the motor's rotational speed.
8	Pos Error -- The error present in the actuator's position.
9	Rate Cmd -- The commanded motor speed.
10	Position Cont Rate Cmd -- The rate command from the position loop.
11	Cmd Generator Output -- Signal generator output that drives the actuator.
12	Slip Gain -- The slip gain constant used by the controller in calculations.
13	Select Waveform -- The command generator waveform type.
14	Cmd Amplitude -- The amplitude of the signal used to drive the actuator.
15	Cmd Frequency -- The frequency of the signal used to drive the actuator.
16	Mode Select -- Represents the command generator mode.
17	DA2 Bias -- The 2nd D/A converter offset voltage adjustment.
18	Ids* -- The commanded flux producing current
19	Kp rate -- The proportional constant for the motor's rate.
20	Ki rate -- The integral constant for the motor's rate.
21	Iqs Limit -- The limit value of the torque producing current, 0-90A RMS.
22	Kp Position -- The proportional constant for the actuators position.

23	DA2 Select -- The number of the signal selected for the output of DA2.
24	DA2 Gain -- The gain of the signal on D/A converter #2.
25	Kprate Limit -- The maximum proportional value Iqs* can change.
26	Ki Position -- The integral position constant.
27	DA2 Bias -- The offset value of D/A converter #2.
28	Act Position (inches) -- Position of actuator relative to the center null position.
30	Motor Counts -- Value in the count register representing motor speed.
31	DA1 Gain -- The gain of the signal on D/A converter #1.
32	LVDT Raw Position-- Actuator binary position before conversion to inches.
33	LVDT Raw Data -- LVDT binary count before evaluation.
34	Overrange Extended -- Indicates that the actuator is over extended.
35	Overrange Retracted -- Indicates that the actuator is over retracted.
36	AD Output -- The value of the input A/D input signal.

3.2.2 Output Variable Description

Time	Unused
Act Pos	The actuator position in reference to the center position.
Act Rate	The rate the actuator is moving.
Motor Rate	The speed of the motor's rotor in RPM.
Cmd	The command amplitude.
Iqs Cmd	The value of the Iqs signal after limiting.
Slip	The slip frequency delivered to the hardware slip counters.
DA2 Output	The commanded voltage output of D to A #2.
Cycle Use	Indicates software cycle use on start up.
Frame Use	Indicates software frame use on start up.

3.2.3 Entering Data

The data is entered onto the data screen using 4 keys. The <ESC> key puts the monitor into the input mode. When in the input mode, data may be entered by using the <C> change key then typing numbers on the keyboard, followed by a <RETURN>. Successive "Values" may be entered by using the <TAB> key to move the cursor down the screen. When the entry of numbers has been completed, the <ESC> key must be toggled again to exit the input mode.

3.2.4 Refreshing the Screen

The monitor screen may be manually refreshed by typing an <R>. This function serves to rewrite the screen with the latest data. If the monitor is in the input mode the refresh will not work. Exit the input mode before attempting to refresh the screen. The output data is updated automatically every 2 seconds.

3.2.5 Operating Guidelines

When the system is first energized the default values listed in section 3.2.1 will be entered into the system. The default mode is actuator position loop control with a square wave drive. The actuator position loop control is the mode in which the actuator system is normally operated. The "Waveform" command selects the type of signal that will be used to drive the actuator. The squarewave and sinewave waveforms are computer generated signals. The "Cmd Ampl" (Command Amplitude) may be adjusted to achieve the desired actuator excursion from the center null position by entering a value up to 5.5 inches. The "Cmd Freq" (Command Frequency) is the frequency at which the waveform driving the motor/actuator will vary. If a 1.0 is entered for instance, the motor/actuator will reverse direction at a 1 Hz rate. If the Demo or External Input is selected for "Waveform" the "Cmd Ampl" and "Cmd Freq" inputs will have no effect on the system's operation. The Demo mode runs a TVC actuator motion profile based on a typical space shuttle mission. The External Input mode enables the A/D converter on the I/O board as the actuators signal source. An external signal generator is required for operation in this mode.

The "Mode Select" may be changed to operate the system either "open loop" or in the "rate" mode. In the rate mode the motor is commanded to operate at a given speed and all actuator position information is ignored. This mode is useful for motor testing. Care should be taken if the motor is attached to the actuator with the system in the rate mode. Since the controller is ignoring the actuator position information, it may run into the stops. Open loop operation may also be selected. In this mode there is no feedback from either the position sensor in the actuator or the speed sensor in the motor. Note that when the mode select = 1 or 2 (rate mode or open loop mode) that the Cmd Ampl must be entered in K-RPM. For example if Cmd Ampl=2 is entered, the motor rate will be 2000 RPM.

Initially, the I_{qs}^* and I_{ds}^* currents are commanded to very low levels by the start up program resident in the single board computer. This is necessary to prevent damage to the power stage upon powering up of the high voltage. After the 20 KHz voltage has been increased to its operating level the I_{qs} and I_{ds} currents may be increased to the desired level. Note that the KpLim (Rate) default value is 20 A. This means that the maximum step change in I_{qs} is limited to 20 A. Most operating modes of the system will require that this value be increased. The remaining default values for the control constants are set to provide a frequency response to meet the Space Shuttle Main Engine TVC requirements. These may

be adjusted as required to modify the response characteristics. The position command of the actuator is available as a test point on the output of DA1 converter. The gain of this signal may be adjusted by inputting the desired value at the DA1 Gain input field on the monitor. The second D to A converter (DA2) may be used to monitor one of 36 signals. DA2's output is selectable from the monitor keyboard. Its default value (6) is the "Digitally Derived Rate" or the speed of the motor. Reference Appendix D "DA output" block diagram and section 3.2.1.1. When the system is operating the output section of the Motor Control Panel will indicate the operating conditions. This information is updated every 2 seconds.

The motor controller and actuator require no extra cooling providing that the system is operated under conditions similar to the Space Shuttle Main Engine Actuator's typical mission; up to 10 minutes at less than a 2% duty cycle. The power stage unit should be operated with the cold plate activated and the motor's cooling air turned on if extended operation is anticipated. The motor's stator temperature may be monitored by connecting a temperature meter to the thermocouple in the stator.

4. SUMMARY OF EXPERIMENTS AND LESSONS LEARNED

Over the course of the 40 HP EMA project there have been several test sessions. The first comprehensive testing of the system was performed at NASA Marshall Space Flight center in Huntsville, Alabama in September of 1992. The second set of tests was performed at GDSS in San Diego in the Summer of 1993. Please refer to the 40 HP Electro-Mechanical Actuator Test Report (August 1993) for a detailed account of the GDSS test results.

In brief, the system has not been tested to full power at this date. The motor however, has been tested to power levels of about 15 HP into a dynamometer load. The entire system's small signal frequency response has been tested both at NASA and GDSS. In both cases the response met the Space Shuttle Main Engine small signal TVC actuator requirements. The measured response at actuator excursions of $\pm 0.1^\circ$ is 3.2 Hz (90 degree phase shift). This measurement was performed with 70 A/phase of motor current. It should be noted that the frequency response is limited by the software and not by the controller's hardware. The frequency response may be extended by modifying the software control constants.

The system was not tested at full power because of 20 KHz link instability. As the motor currents are increased, the 20 KHz link voltage begins to change in both amplitude and phase. In extreme cases this is a destructive situation as the link voltage increases to levels that exceed the peak operating voltage of the power stage switches and capacitors. The phase shift triggers improper timing of the output switches leading to potential voltage spikes. In an effort to reduce and/or eliminate this problem several options were investigated.

It was proposed that a filter in line with each of the three motor phases might reduce the 20 KHz link instability. The filter, designed with a low cutoff frequency of about 1 KHz was expected to smooth out the ripple currents contributing to the link instability. In practice, the stability of the 20 KHz link was improved by the addition of this filter. It did not improve sufficiently to allow full power testing, however. A secondary effect created by insertion of the filter is a phase shift of the motor currents. The resulting modifications required to mitigate the phase shift introduced by the filters were prohibitive. Finally, the filter was abandoned as a solution to the problem.

The research on the filter circuit did indicate that the 20 KHz link performance could be improved by adding inductance into the motor lines. This increased inductance limits the motor current's di/dt and subsequently reduces the link instability. The final testing of the actuator did in fact include a 200 μ H choke in line with each of the three motor phases. The inclusion of the chokes in the circuit reduces the voltage available at the motor terminals by an amount in proportion to the ratio of the motor's leakage inductance to the chokes inductance value. This reduces the motor's output power unless the link voltage is increased to compensate for the lower motor voltage. Calculations indicate that a choke value of 150 μ H and a link voltage of 350 VRMS should allow full power operation of the system.

The instability of the 20 KHz link voltage has since been determined to be caused by the effects of reactive power in the system. Under certain conditions reactive energy is forced from the motor, back into the 20 KHz inverters. During these periods the 20 KHz bus voltage increases by as much as 50%. The condition is oscillatory and the voltage reaches a minimum value a cycle of two later before settling out. Several methods have been proposed that may remedy this situation by controlling the reactive energy. These methods are further explained in the "Recommendations" section.

Several important lessons were learned in regard to the design of the motor controller power stage. The first power stage design suffered from switching problems due to excessive inductance in the IGBT switch circuit. This problem was corrected by changing the current carrying wires to copper bars. This lowered the inductance and the switching problems were greatly reduced. The problem was completely eliminated by redesigning the power stage and driver boards as part of a 40 HP Retrofit Design, completed in December of 1992. This design incorporated modular IGBT's in place of the discrete parts used in the first design. The modular design of the IGBT's allowed shorter distances between connections and a lower overall inductance in the power stage. The driver boards were also redesigned at this time to increase the IGBT gate drive voltage and improve isolation to the output stage. The increased gate drive voltage improved the noise immunity of the driver circuitry substantially.

5. RECOMMENDATIONS

There are several areas in which design modifications may aid the performance of the system. The first is the motor's current regulator. The present current regulator is a "bang bang" regulator. The circuitry is designed to respond to discrete current level changes only. If the current is within range of its "window" no action is taken. A simulation performed by Kraus and Associates for NASA LeRC indicates that in the 40 HP system, the motor currents shall never reach their commanded steady state values with this type of current regulator. Their simulations indicated a significant limitation in the torque output of the motor under these conditions. This has been confirmed in measurements performed on the system as well. The motor never produces the torque values expected, relative to the commanded currents. Kraus and Associates suggested the incorporation of a PI current regulator into the hardware to correct this deficiency.

The second area of inadequate performance is the 20 KHz link stability. Several ideas have been proposed to improve the performance of the motor controller with the 20 KHz inverters. The first is to change the switch state selection circuitry in the motor controller power stage so that reactive currents are not forced back onto the 20KHz link. This requires a modification to the EPROM and adjoining circuitry that control the switch states. Another idea expands on the first by adding additional switch states as part of the modification. The extra switch states are achieved by using the motor's neutral connection in addition to the 3 phase terminals. Connecting between the neutral and one of the 3 phase terminals reduces the required terminal voltage by a factor of 1.73. Thus the voltage fluctuations are less likely to exceed the maximum voltage ratings on the components. In addition the extra switch states provided by this arrangement allow superior control of the motor's currents. This change requires substantial extra power stage circuitry consisting of IGBT's and new driver circuits.

A means to stabilize the output of the 20 KHz inverters may also be investigated. Further research into the operation of the inverters should yield potential inverter modifications that provide a "stiffer" voltage source to the load. The ultimate solution may be a combination of the design modifications outlined here.

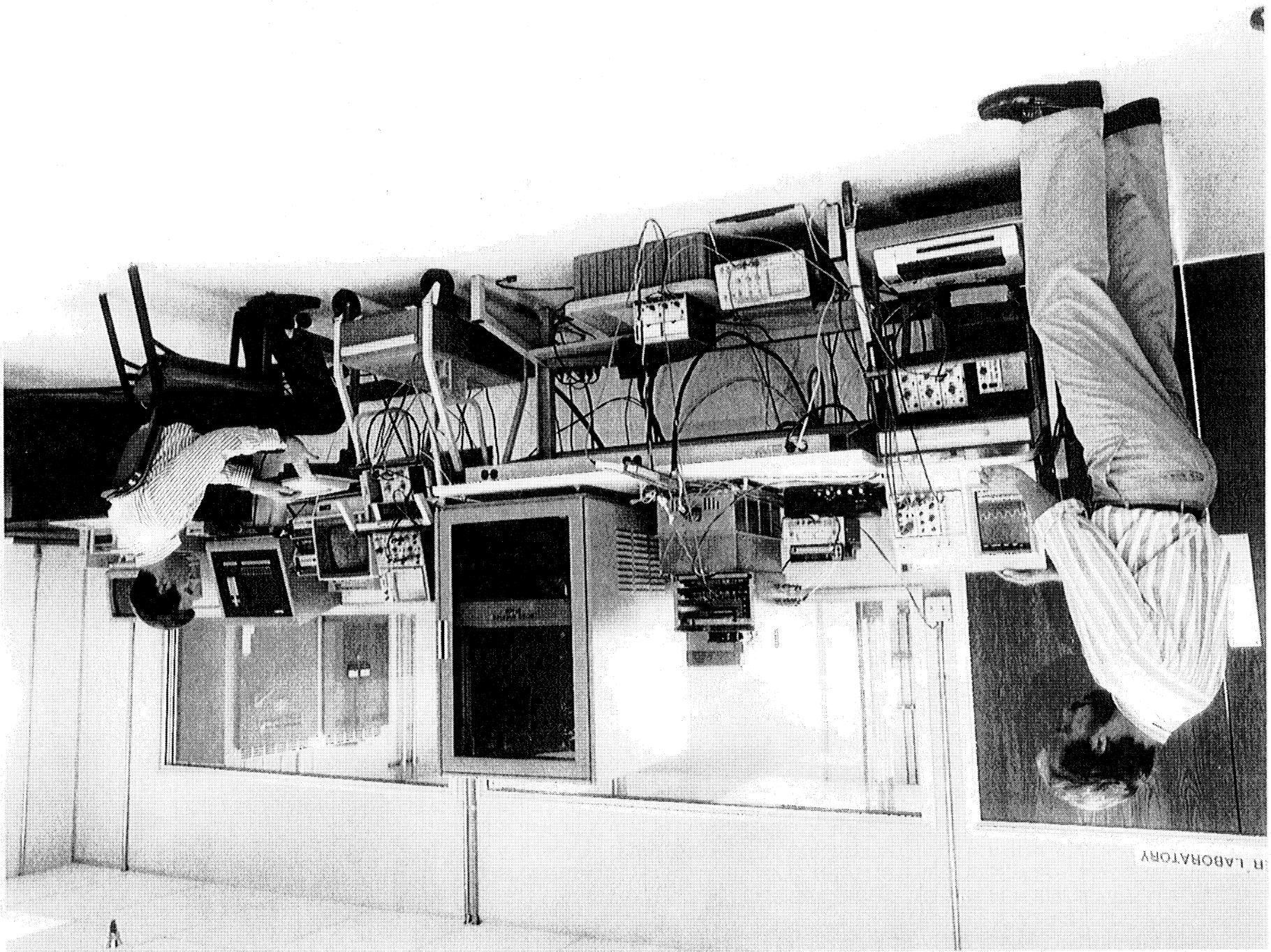
APPENDICES

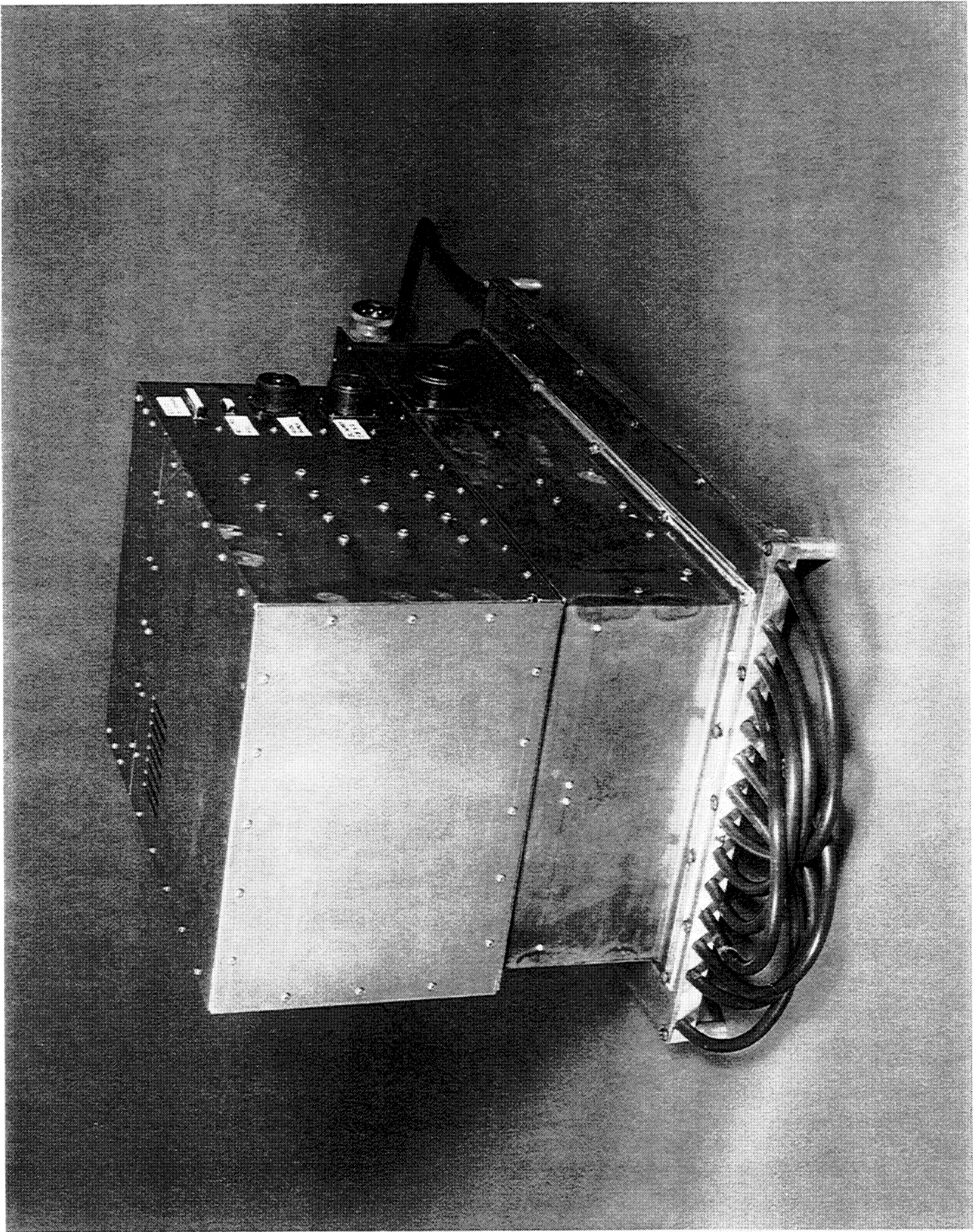
<u>Appendix</u>	<u>Title</u>
A	Motor Controller Card Cage and Power Stage
B	Moog Actuator with Sundstrand Motor
C	Actuator and Motor Specifications
D	Digital to Analog Converter MATRIXx Diagram
E	References

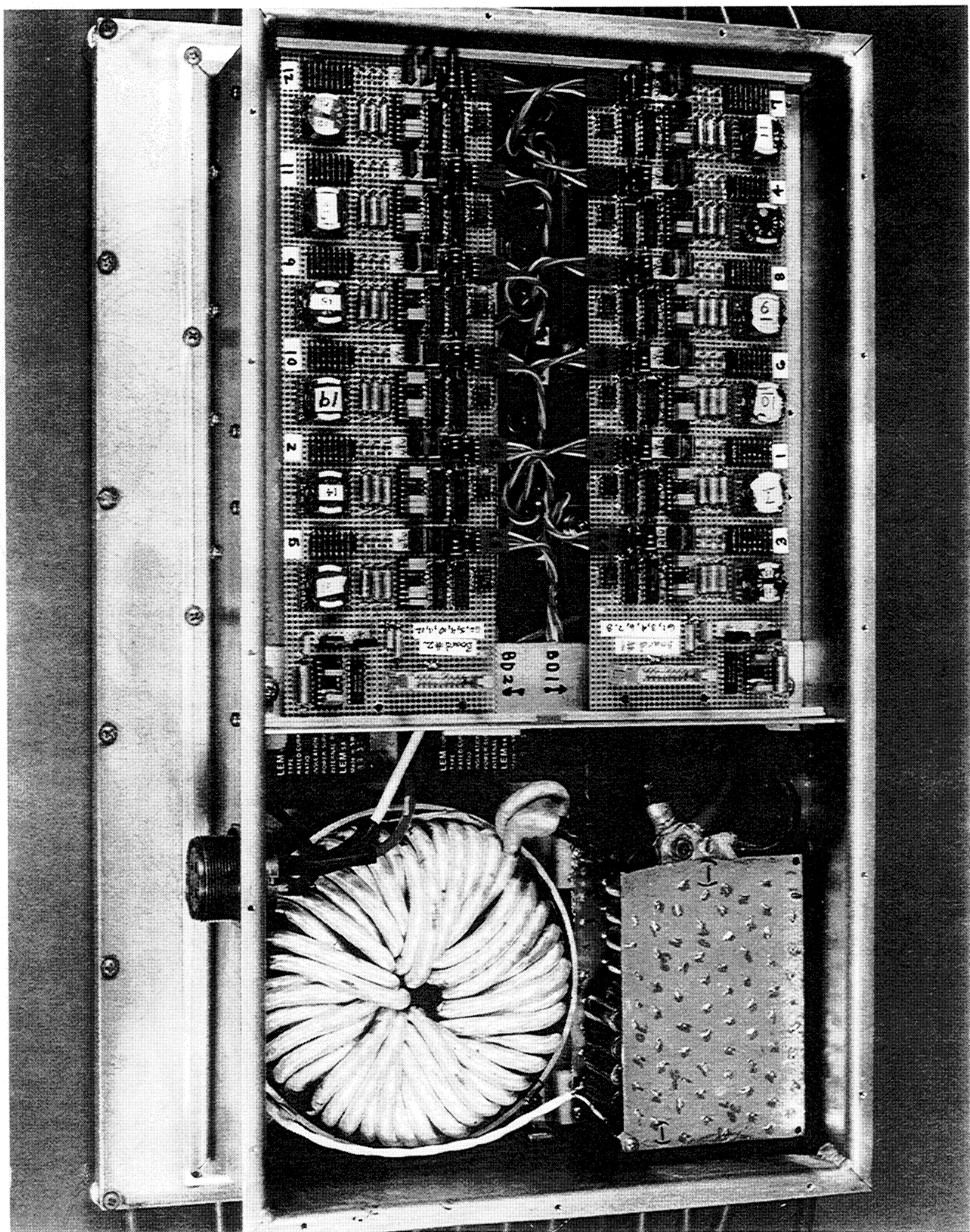
APPENDIX A

Motor Controller Card Cage and Power Stage

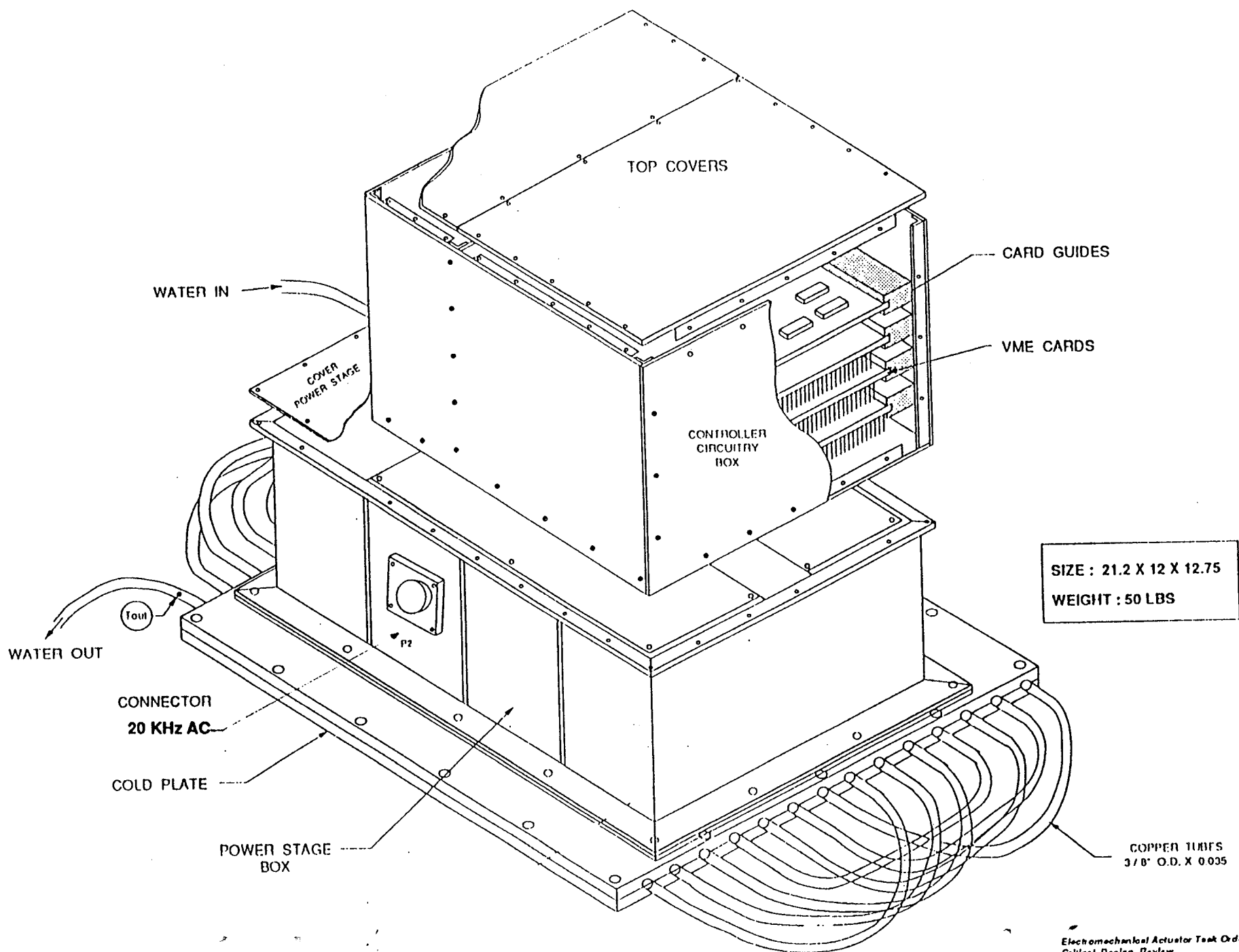
- (1) Laboratory showing Motor Controller, AC Inverter, Input terminal, Low Voltage Power Supply.
- (2) Motor Controller Card Cage mounted on top of Power Stage and Cold Plate.
- (3) Top View of the Power Stage (Cover Removed).
- (4) Drawing; Motor Controller Card cage, Power Stage, and Cold Plate.
- (5) Drawing; VME Backplane Detail
- (6) Drawing; Motor Controller Top View (Cover Removed)





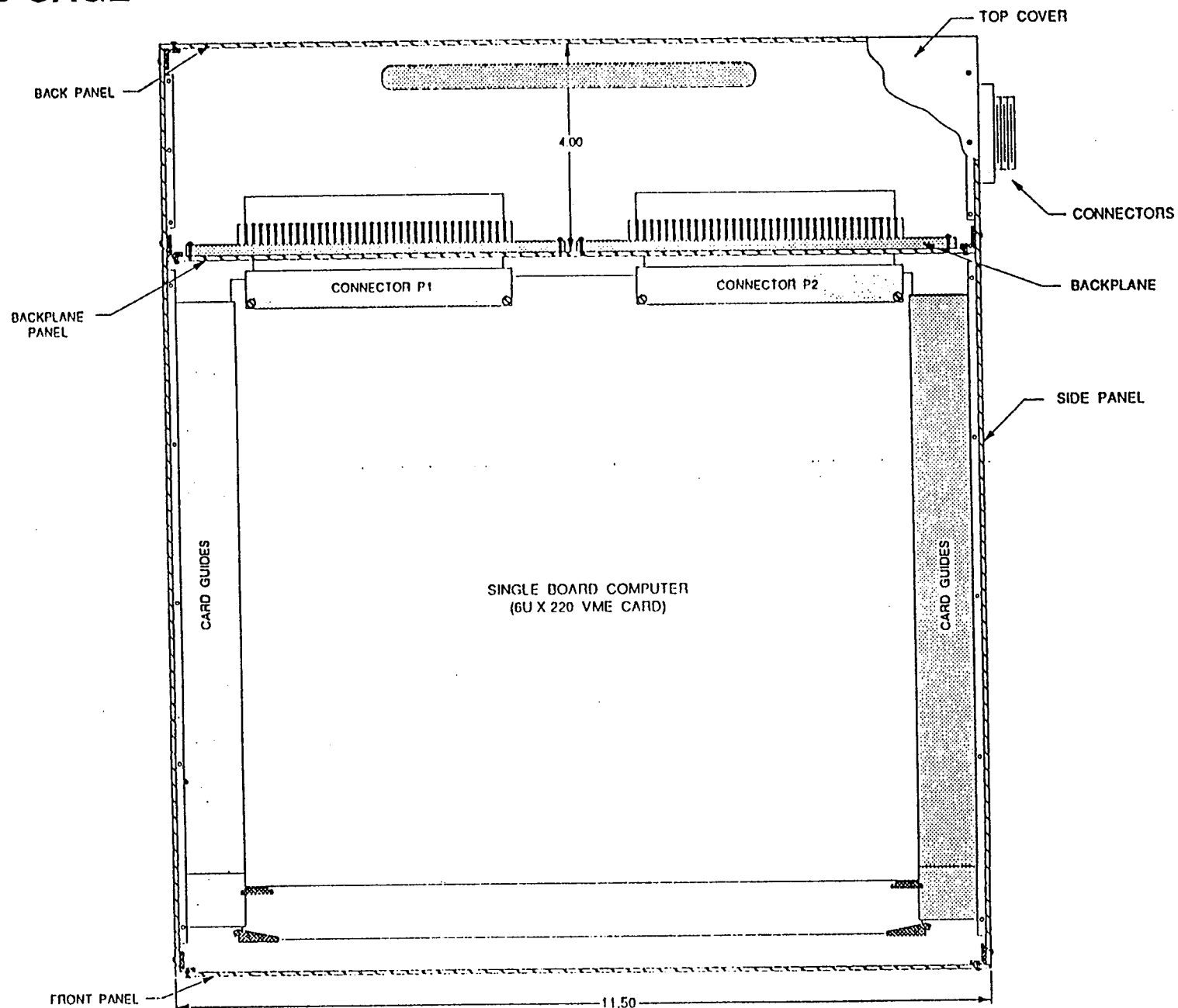


40 HP EMA MOTOR CONTROLLER LAYOUT



40 HP EMA MOTOR CONTROLLER

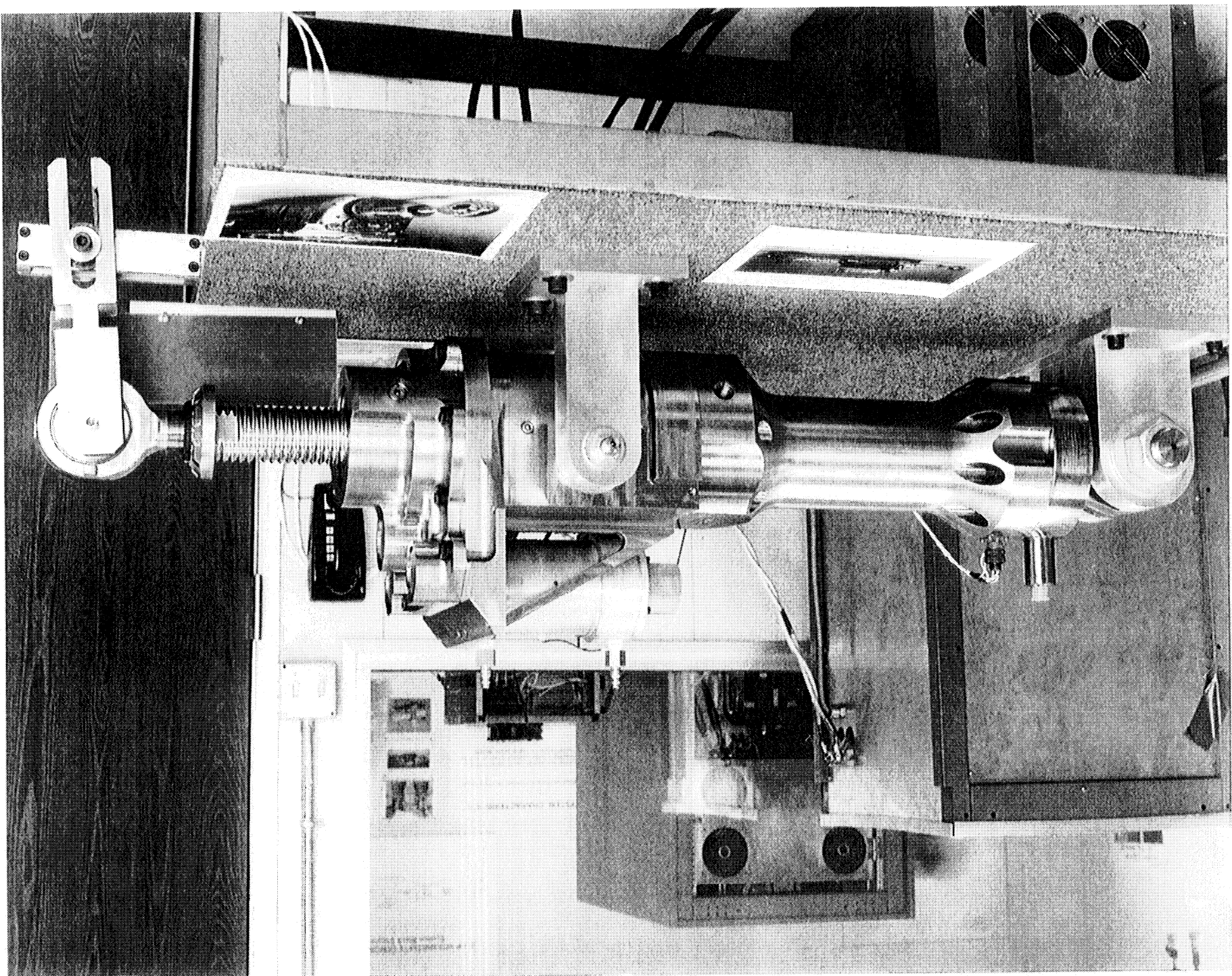
VME CARD CAGE



TOP VIEW

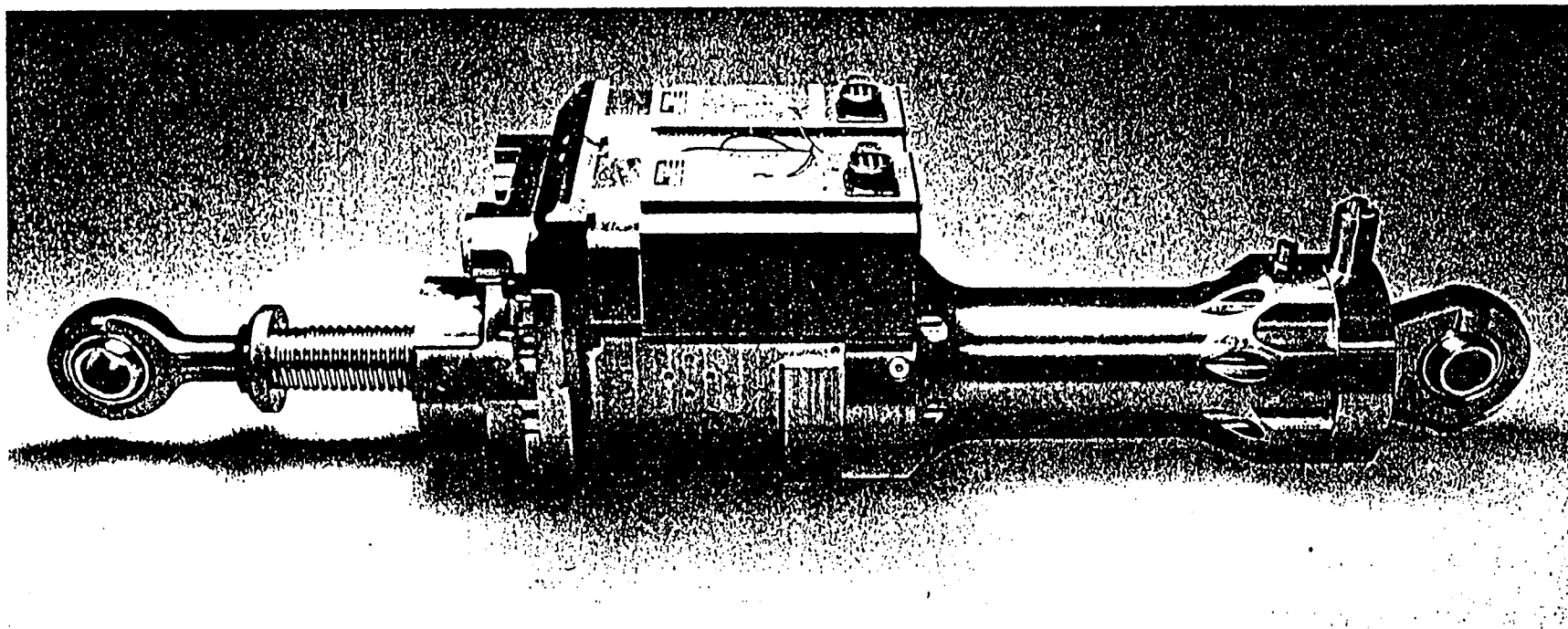
APPENDIX B

Moog Actuator with Sundstrand Motor



APPENDIX C

Actuator and Motor Specifications



OUTPUT TRAVEL ± 5.5 IN
 STALL FORCE 48,000 LB
 MAXIMUM IMPULSE LOAD 100,000 LB
 ACCELERATION 60 IN/SEC^2

RATED POWER 38 HP
 - OUTPUT FORCE 48,000 LB
 - OUTPUT VELOCITY 5.2 IN/SEC
 DUTY CYCLE 10 MIN
 - AVERAGE LOAD 15,000 LBS

Electromechanical Actuator Dual Torque - Summed Motors

MOTOR PERFORMANCE PARAMETERS

MADAN BANSAL

PERFORMANCE PARAMETERS

POWER SUPPLY:

- 0 - 120 VAC (L - N)
- 0 - 750 HZ
- 15,000 RPM, MAXIMUM SYNCHRONOUS SPEED

LOAD:

- 7.4 IN./SEC. LINEAR MAXIMUM VELOCITY
- 1.64 IN./SEC. NORMAL LINEAR VELOCITY
- 52 IN./SEC.² LINEAR ACCELERATION
- 185,150 LB./FT.² ENGINE INERTIA
- 24,500 LB. NORMAL OPERATING FORCE
- 31,300 LB. FORCE DURING ACCELERATION
(INCLUDING EFFECT OF ENGINE INERTIA)

PERFORMANCE PARAMETERS

DUTY CYCLE:

NORMAL POWER	-	99%
MAXIMUM POWER	-	1%
TOTAL MISSION TIME	-	600 SEC.
BEARING LIFE	-	10,000 HR.
INSULATION LIFE	-	10,000 HR.

ACCESSORIES:

RESOLVER - HAROWE MODEL #21BRCX-335-512

THERMAL PROTECTION - ONE IRON - CONSTANTAN
THERMOCOUPLE IN STATOR IRON

ACCESS HOLE FOR ROTOR TEMPERATURE MEASUREMENT

FLANGE MOUNTING

PROVISION FOR AIR COOLING DURING DEMO

PERFORMANCE PARAMETERS

GEAR & ACTUATOR:

- 0.80 EFFICIENCY
- 203.81 RAD./IN. - GEAR RATIO
- 0.0077 LB.IN.SEC² - INERTIA AT MOTOR SHAFT
- ZERO IMPACT LOAD ON MOTOR DURING ENGINE START
- ZERO LOAD ON MOTOR BEARING DUE TO GEAR

ACCELERATION:

- 0.02764 LB.FT.² MOTOR ROTOR INERTIA (IM)

$$TAC = \frac{240174}{NM} + 0.022815 \text{ nm Im LB. FT.}$$

NM

$$AT \text{ NM} = 14700 \text{ RPM}$$

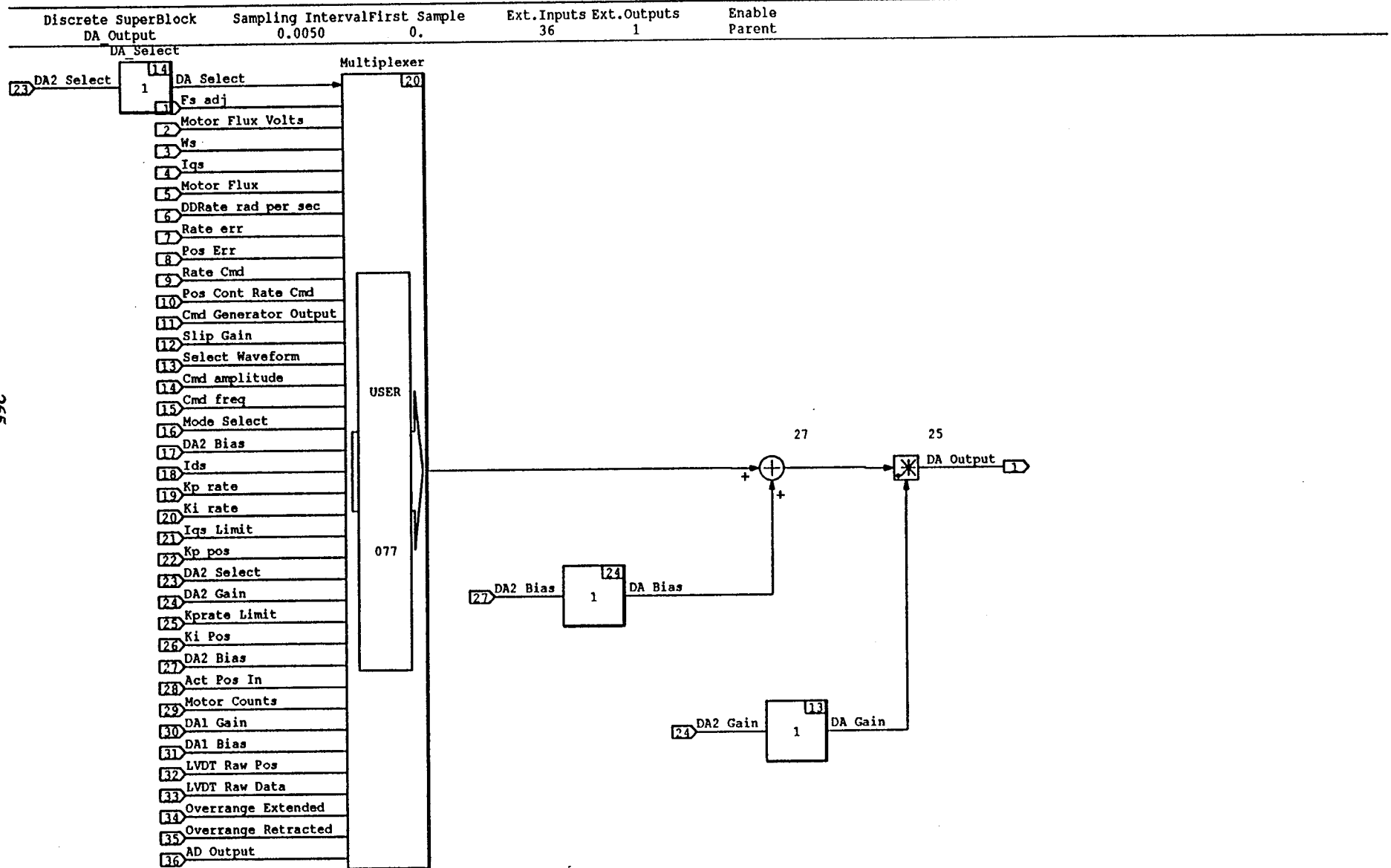
$$TAC = 307.3 \text{ LB.IN.}$$

APPENDIX D

Digital to Analog Converter MATRIXx Diagram

03-SEP-93

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APPENDIX E

References

<u>TITLE</u>	<u>DATE</u>
40 HP Electro-Mechanical Actuator Test Report NASA Contract: NAS325799, GDSS	August 1993
40 HP EMA Hardware Documentation NASA Contract: NAS325799, GDSS	December 1993
40 HP EMA Software Documentation NASA Contract: NAS325799, GDSS	November 1993
Investigation of Advanced Power Sources and Actuator Systems for Future Aerospace Vehicles. Technical Progress Report, P.C. Krause and Associates Inc.	March 1993
Investigation of Advanced Power Sources and Actuator Systems for Future Aerospace Vehicles. SBIR2-NAS-R6 P.C. Krause and Associates Inc.	March 24, 1992
Study of Generator / Motor Operation of Induction Machines in a High Frequency Link Space Power System. NAG3-631 University of Wisconsin, Madison. Report # 179600	March 1987

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13. ABSTRACT (Maximum 200 words) This report summarizes the work performed on the 40 HP electro-mechanical actuator (EMA) system developed on NASA contract NAS3-25799 for the NASA National Launch System and Electrical Actuation (ELA) Technology Bridging Programs. The system was designed to demonstrate the capability of large, high power linear ELAs for applications such as Thrust Vector Control (TVC) on rocket engines. It consists of a motor controller, high frequency power source, drive electronics and a linear actuator. The power source is a 25kVA 20 kHz Mapham inverter. The drive electronics are based on the pulse population modulation concept and operate at a nominal frequency of 40 kHz. The induction motor is a specially designed high speed, low inertia motor capable of a 68 peak HP. The actuator was originally designed by MOOG Aerospace under an internal R & D program to meet Space Shuttle Main Engine (SSME) TVC requirements. The design was modified to meet this programs linear rate specification of 7.4 inches/second. The motor and driver were tested on a dynamometer at the Martin Marietta Space Systems facility. System frequency response and step response tests were conducted at the Marshall Space Flight Center facility. A complete description of the system and all test results can be found in the body of the report.				
14. SUBJECT TERMS Electromechanical actuator; Resonant converters; Induction motor; Launch vehicles		15. NUMBER OF PAGES 270		
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